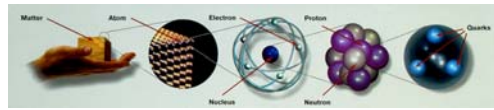
From the last time

- The hierarchy or matter
  - Large to small: tables, molecules, atoms, proton neutrons electrons
  - Previously discussed protons neutrons and electrons and the forces to understand matter
- Would like to understand what is fundamental. The smallest indivisible building blocks and the forces to put them together
- Quarks and leptons and the four forces
  - Whole structure of matter can be understood from the quarks and leptons - along with the forces
  - Understood in terms of quantum field theory of particles, fields and forces

Essay due Friday: Please include citation to reference
HW 10: Chap 18 - Conceptual 6, 10, 12 - Problems 2, 4

What have we learned?

Matter is made of atoms



Atoms are made of leptons and quarks

Leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ Quarks $\begin{pmatrix} u \\ d \end{pmatrix}$

Interact via different forces carried by particles, Electromagnetic - photon, also strong, weak, gravity

Generations - Times 3

- Three generations

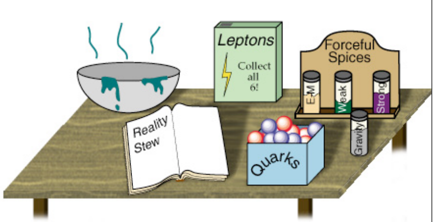
Generation I	Generation II	Generation III	
e^-	μ^-	τ^-	-1
ν_e	ν_μ	ν_τ	0
			Charge
d	s	b	+2/3
u	c	t	-1/3

Question

The difference between the different generations of leptons or quarks is

A. their charge
B. their mass
C. their color
D. their spin

The Standard Model



- 6 leptons
- 6 quarks
- Today: 4 interactions
  - Electromagnetic, Gravitational, Strong, Weak
  - 'mediated' by 13 exchange bosons, which are excitations of the corresponding fields.

EM interaction

- Charged particles interact via the electromagnetic (EM) interaction
  - A charged particle couples to the photon field
  - It excites a photon (excited state of photon field) and loses energy.
  - Another charged particle can absorb the energy from the photon field (photon disappears).

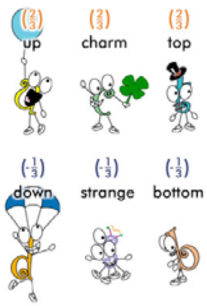
Only particles with an electric charge couple to the photon field.

Strong force and the Quarks

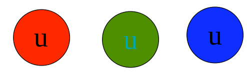
Six different kind of quarks, analogous to the six leptons

All quarks have an electric charge, they couple to photon field.

But they also have a 'color' charge, and they couple to the gluon field



Coupling of quarks to the gluon field is the 'strong' interaction

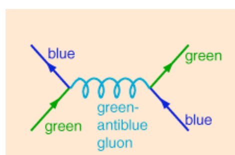


Quarks & Gluons

1. There are three color charges
2. Gluons are the carrier of the strong force
3. They keeps quarks bound up inside hadrons
4. Gluons themselves carry color, they can interact with each other!

Quark interactions: gluons

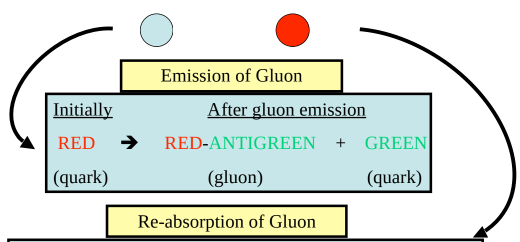
- Gluon carries color charge.
- So when a quark emits a gluon, it changes color.
- But this also means that gluons can interact via the color force.



Feynman diagram for an interaction between quarks generated by a gluon.

Each of the 8 color combinations have a "color" and an "anti-color"

Interactions through Exchange of Color Charge



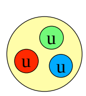
Emission of Gluon

Initially		After gluon emission		
RED	➔	RED-ANTIGREEN	+	GREEN
(quark)		(gluon)		(quark)

Re-absorption of Gluon

Before gluon absorption			After gluon absorption
RED-ANTIGREEN + GREEN		➔	RED
(gluon)	(quark)		(quark)

Why Three Colors?



Remember the Delta baryon, or Δ^{++}

The quarks are fermions:
Fermions are identical and are not allowed to be in the same state. The wave function would disappear.

The electrons in an atom could be in the same energy state if they had different spins.

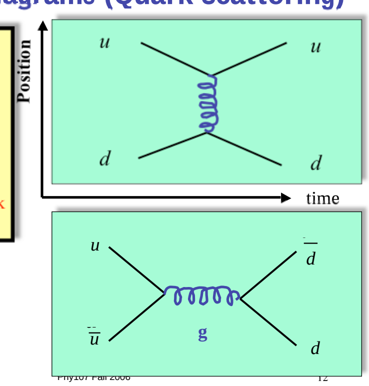
The same same is true of three quarks if something is different about them. Color!

Feynman Diagrams (Quark Scattering)

Quark-quark **Scattering**

Could also be Quark-antiquark **Scattering** or Antiquark-antiquark Scattering

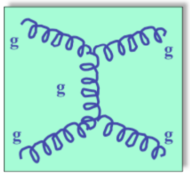
Quark-antiquark Annihilation



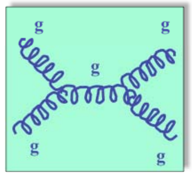
Gluon interactions

Since gluons carry "color charge", they can interact with each other !
(Photons can't do that)

Gluon-gluon Scattering

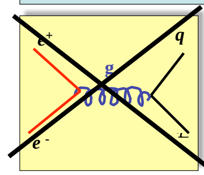


Gluon-gluon Fusion



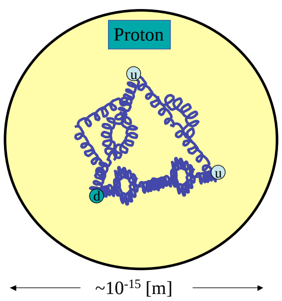
Gluons - Important Points

- Gluons are the "force carrier" of the strong force.
- They only interact with object which have color, or color charge.
- Therefore, gluons cannot interact with leptons because leptons do not have color charge !



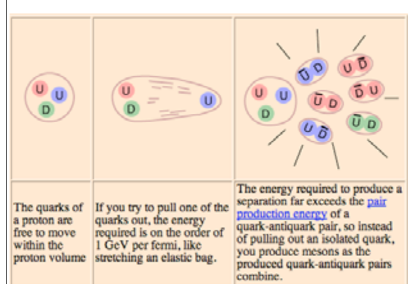
This cannot happen, because the gluon does not interact with objects unless they have color charge!
Leptons do not have color charge !

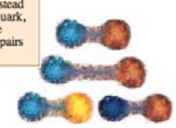
Gluons in the hadrons.



- The gluons are all over inside hadrons!!
- In fact there are a lot more than shown here !!!
- That's where the extra mass comes from. u and d quarks are 0.003 and 0.006 and the proton 1 GeV

Confinement



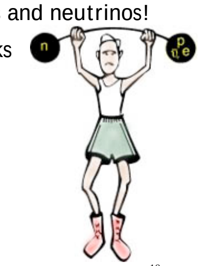


Comparison Strong and EM force

Property	EM	Strong
Force Carrier	Photon (γ)	Gluon (g)
Mass	0	0
Charge ?	None	Yes, color charge
Charge types	+, -	red, green, blue
Mediates interaction between:	All objects with electrical charge	All objects with color charge
Range	Infinite (∝ $1/d^2$)	10^{-14} [m] (inside hadrons)

The weak interaction

- Weak interaction is 'not strong', but is important. It can change one particle into another!
- Muon, tau, can turn into leptons and neutrinos!
- Quarks can turn into other quarks
- Particles with a 'weak charge' (quarks and leptons) couple to the 'weak field'
- Excitations of the weak field are the *Z* and *W* bosons.



Importance of weak interaction

- Weak interaction is much weaker than strong and electromagnetic interactions
- But it's existence is of great importance, as well as its strength.
- Fusion in the sun:
  - First part is hydrogen ->into heavy hydrogen (deuterium),
  - Caused by by the weak force. Without this force solar energy production would not be possible.
  - If weak force been stronger, sun's life span too short for life to have had time to evolve on any planet!
- Practical applications
  - Radioactive elements used in medicine and technology (Usually beta-radioactive), and in the beta-decay of carbon-14 (carbon-dating)

Question

Quarks interact only via the

A. weak force
B. strong force
C. gravitational force
D. all of the above

Carriers of the weak force

- Like the Electromagnetic & Strong forces, the Weak force is also mediated by "force carriers".
- For the weak force, there are **three** force carriers:

W^+ W^- — These "weak force" carriers carry electric charge also !

Z^0 — This "weak force" carrier is electrically neutral

The "charge" of the weak interaction is called "weak charge"

Massive particles

- The W^+, W^-, and Z^o are very massive

W^+ W^-: 80.4 Mev/c^2

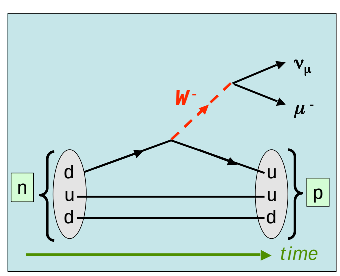
Z^o: 91.2 Mev/c^2

W and *Z* have almost half the mass of the top quark, the heaviest fundamental particle

What interacts?

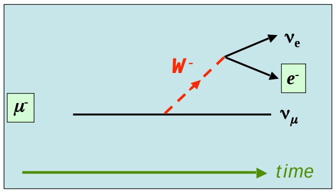
- Any particle with a 'weak charge' will interact via the weak interaction.
- All quarks and leptons carry a weak charge.
- The weak interaction occurs by exchanging a W^+ , W^-, or Z^o
- But all quarks have electric charge, and half the leptons do.
- In this case, weak interaction overwhelmed by electromagnetic interaction.

What Can happen



- Weak radioactive decay
- W carries away -1 charge and decays to a muon and a muon neutrino
- The strangest interaction - it converts particles from one type to another
- Flips the flavor

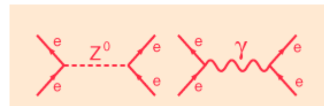
Convert the Paritcles



- Can convert muons into electrons.
- This is what we often see it do. Convert heavier leptons and quarks into lighter ones.

Exchanging the Z^o

- Both of these contribute to the total interaction between electrons
- Z^o is uncharged particle like the photon, but has mass.
- But the electromagnetic interaction is much larger.



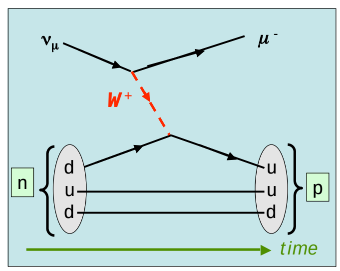
Neutral weak int.	Electromagnetic int.
• Zero charge • Mass ~ 90 GeV / c^2 • Range ~ 10^{-18} m	• Zero charge • Mass = 0 GeV / c^2 • Range ~ inf.

The Neutrino

Why can the neutrino pass through light years of material without interacting with anything.

A. It has no mass
B. It is very small
C. It interacts only via the weak force
D. It interacts only via the EM force

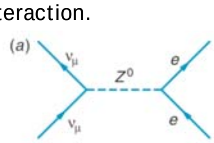
Neutrino into muon



- The neutrino interacts with quarks bound inside nucleons in the nucleus.
- Neutrino emits W^+, changing into muon.
- Down quark bound in a neutron absorbs W^+, changing into up quark.
- The nucleon then has two ups and one down quark, which is a proton.

Neutrinos

- Neutrino has no electric charge
- Interacts **only** via the weak force.
- How weak is weak?
  - Neutrino traveling in solid lead would interact only once every 22 light-years!
  - And weak force only "*kicks in*" for $d < 10^{-18}$ m, a distance ~ 1000 times smaller than the nucleus
- But there are **lots** of neutrinos, so it is possible to observe an interaction.



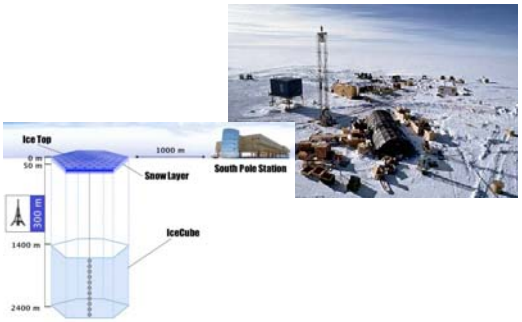
Detecting neutrinos

- Neutrinos interact with all matter, since all matter particles have a weak charge.
- But the interaction is extremely weak
- Need large volumes, sensitive detectors, to see neutrinos.
- Use the neutrino into electron or muon reaction

Examples of neutrino detectors:

Super Kamiokande (Japan)
Ice Cube (UW-Madison at Antartica)

Ice Cube



Changing flavors

- Flavor change can occur spontaneously.
  - Experimentally, this occurs within a lepton generation

Generation I	Generation II	Generation III	Charge
e^- ν_e	μ^- ⇩ ν_μ	τ^- ⇩ ν_τ	-1 ⇩ 0
Electron is stable	Emit W^- 2×10^{-6} seconds	Emit W^- 3×10^{-13} seconds	

Quarks and the weak force

- Quarks have color charge, electric charge, and weak charge — other interactions swamp the weak interaction
- But similar to leptons, quarks can change their flavor (decay) via the weak force, by emitting a *W* particle.

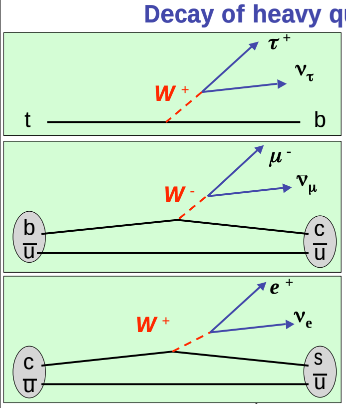
Generation I	Generation II	Generation III	Charge
u d	c ⇩ s	t ⇩ b	+2/3 ⇩ -1/3
	Emit W^+ 2×10^{-12} seconds	Emit W^+ 10^{-23} seconds	

Flavor change between generations

- But for quarks, not limited to within a generation
- Similar to leptons, quarks can change their flavor (decay) via the weak force, by emitting a *W* particle.

Generation I	Generation II	Generation III	Charge
u d	c s	t b	+2/3 ⇧ -1/3
	Emit W^-	Emit W^- 10^{-12} seconds	

Decay of heavy quarks



Top quark decays so fast (10^{-23} s), it doesn't have time to form a meson.
$t \rightarrow b + \tau^+ + \nu_\tau$

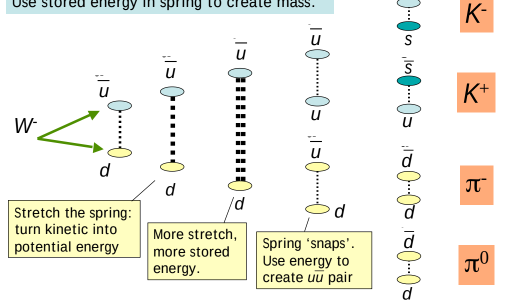
B– particle decays within 1.5×10^{-12} s.
$B^- \rightarrow D^0 + \mu^- + \bar{\nu}_\mu$

The D^0 meson decays within 0.5×10^{-12} s.
This decay:
$D^0 \rightarrow K^- + e^+ + \nu_e$

But it can be more complicated

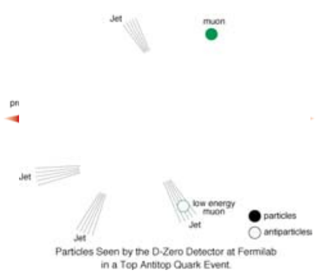
Think of the gluons being exchanged as a spring… which if stretched too far, will snap! Use stored energy in spring to create mass.

Hadrons!



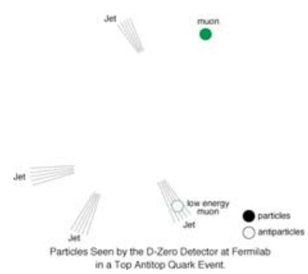
Top quark discovery 1995

- Proton-antiProton collision at Fermilab
- Only final decay products are observed.
- Infer existence of other particles by thinking about decays.



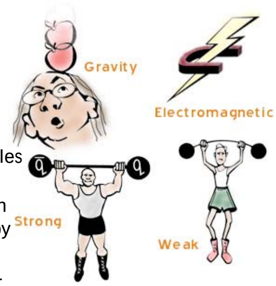
What the detector sees

- These are the only objects observed.
- Everything else must be extrapolated.
- Build on known reactions.



Four interactions

- The four fundamental interactions all have associated fields and mediating particles.
  - EM interaction between electrically charged particles by exchange of photons
  - Strong interaction between 'color' charged particles by gluon exchange
  - Weak - radioactive decay - part of fusion in the sun



Particles & their Interactions (Summary)

	quarks	Charged leptons (e,μ,τ)	Neutral leptons (ν)
Color Charge ?	Y	N	N
EM Charge ?	Y	Y	N
'Weak' Charge ?	Y	Y	Y

- ❑ Quarks can participate in Strong, EM & Weak Interactions.
- ❑ All quarks & all leptons carry weak charge.
- ❑ Neutrinos only carry weak charge.

Comparison of the Force Carriers

	EM	Strong	Weak	
Force Carrier	**Photon (γ)**	**Gluon (g)**	**W^+, W^-**	**Z^0**
Charge of force carrier	None	Color	Electric	None
Couples to:	Particles w/elect. charge	Particles w/color charge (Quarks,gluons)	Particles w/weak charge (Quarks, leptons, W,Z)	Particles w/weak charge (Quarks, leptons W,Z)
Range	Infinite ($1/d^2$)	$<10^{-14}$ m (inside hadrons)	$< 2\times10^{-18}$ m	$< 2\times10^{-18}$ m

Unification

- It may be possible that all quarks and leptons can be viewed as different components of the same particle.
- Also may be possible to **unify** the forces (exchange bosons).
- Electromagnetic and Weak force have already been unified (next time).
- People working hard to include the strong force and gravitational force in this.