From Before…

- Discussed the weak interaction
- All quarks and leptons have a 'weak charge'
  - They interact through the weak interaction
- Weak interaction often swamped by electromagnetic or strong interaction.
- Most clearly manifested in particle decays, where the weak interaction can change one particle into another.

Essay Due Today

EM interaction

- Charged particles interact via the electromagnetic (EM) interaction
  - A charged particle couples to the photon field
  - It can also excite a photon (excited state of photon field) and lose 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.

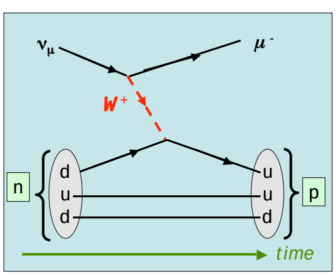
Strong interaction

- Particles with color charge interact via the strong interaction
  - A color charged particle(red, blue, green) couples to the gluon field.
  - Includes quarks and gluons
  - Fact that gluons can interact with other gluons leads to some interesting effects.
  - Confinement, particle creation, range of the strong force.
    - Pulling apart quarks takes a large amount of energy. Like a very strong spring. Actually a string of gluons.
    - That energy can be used to make other particles, $E=mc^2$.
    - Leads to short range of force

Weak interaction

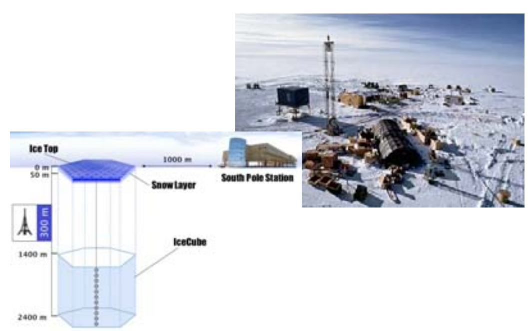
- Particles with weak(flavor) charge interact via the weak interaction
  - A flavor charged particle couples to the W+, W- and Z fields.
  - Includes all matter particles. Neutrinos can only interact via the weak force
  - Strangest force. Only force that changes particles involved. Change must conserve charge and mass/energy.
  - For the W can be thought of as flipping the flavor:
    - From up to down, from massive lepton to neutrino
  - Most often noticed when the weak force in the only force that can act on the system. Neutron to proton, neutrinos
  - Massive nature of W and Z make weak force short lived and weak, $\Delta E \Delta t \sim h$

Neutrino into muon



- Neutrino has no electric or color 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.
- This is our method or studying the sun

Ice Cube



Changing flavors

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

Generation I	Generation II	Generation III	Charge
e^-	μ^-	τ^-	-1
⇓	⇓	⇓	⇓
ν_e	ν_μ	ν_τ	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.

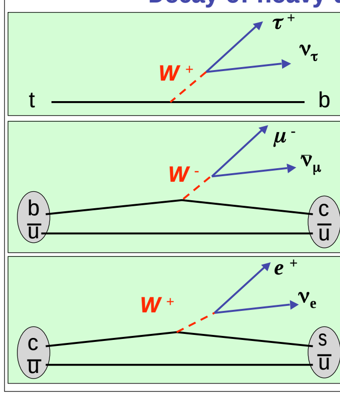
Generation I	Generation II	Generation III	Charge
u	c	t	+2/3
	⇓	⇓	⇓
d	s	b	-1/3
	Emit W^+ 2×10^{-12} seconds	Emit W^+ 10^{-23} seconds	

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 ⇖	c ⇖	t	+2/3
			⇑
d	s	b	-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.
$t \rightarrow b + \tau^+ + \nu_\tau$

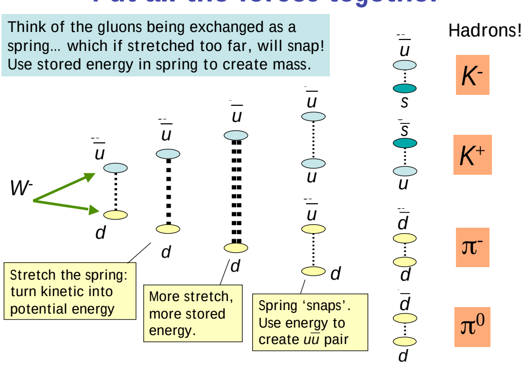
B⁻ particle decays within 1.5×10^{-12} s.

$B^- \rightarrow D^0 + \mu^- + \bar{\nu}_\mu$

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

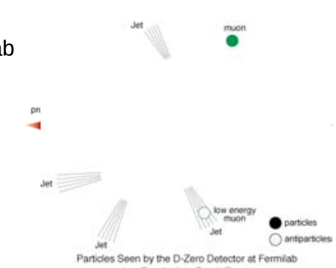
Put all the forces together

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



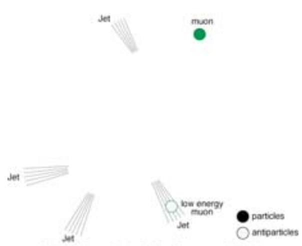
Top quark discovery 1995

- 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.



Particles Seen by the D-Zero Detector at Fermilab in a Top Antitop Quark Event

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

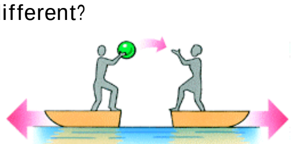
	EM	Strong	Weak	
Force Carrier	Photon (γ)	Gluon (g)	W^+, W^-	Z^0
Charge of force carrier	None	Color	Electric	None
Couples to:	Particles w/elect. charge	Particles w/color charge (Quarks,gluons)	Particles w/weak charge (Quarks, leptons, W,Z)	Particles w/weak charge (Quarks, leptons W,Z)
Range	Infinite ($1/d^2$)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

Something interesting about the weak interaction

- As far as the weak interaction goes, leptons and quarks are basically identical.
- All carry a weak charge.
- All six quarks can change flavor via the weak interaction. Within a generation or between generations.
- Leptons can change flavor within a generation, and neutrinos between generations(discovered recently by looking at neutrinos from the sun).
- So maybe all quarks and leptons are just different 'states' of the same 'master particle'

And several different interactions

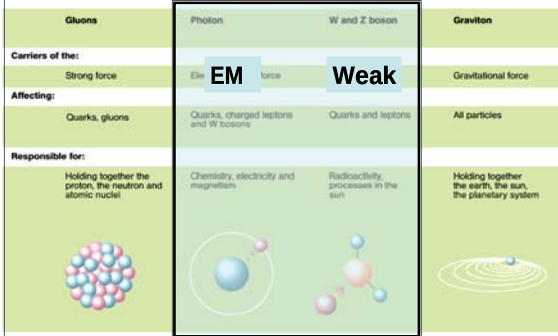
- Remember that interactions are due to exchange of bosons.
- EM interaction - exchange photons
- Weak interaction - exchange W^+, W^-, Z^0
- Strong interaction - exchange gluons (8)
- But are they so different?



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.
- People working hard to include the strong force and gravitational force in this.

Exchange Bosons (force carriers)

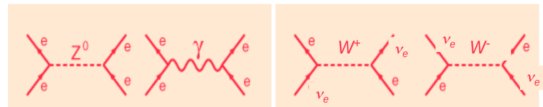


Electro-weak unification

The standard model says that

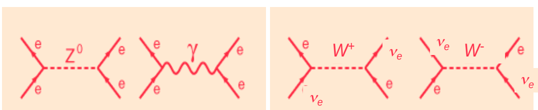
the electromagnetic interaction (photon exchange) &
the weak interaction (W^+, W^-, Z^o exchange)

are different pieces of the same **electroweak** interaction



Neutral weak	Electromagnetic	Pos. weak	Neg. weak
• Zero charge	• Zero charge	• Pos. charge	• Neg. charge
• Mass=91 GeV/c^2	• Mass=0 GeV/c^2	• Mass=80 GeV/c^2	• Mass=80 GeV/c^2
• Range ~ 10^{-18} m	• Range ~ inf.	• Range ~ 10^{-18} m	• Range ~ 10^{-18} m

Some similarities here



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These two both
exchange neutral bosons
Neither boson
changes the lepton flavor
(remains electron)

These two both
exchange charged bosons.
Both bosons
change the lepton flavor

Similar indeed

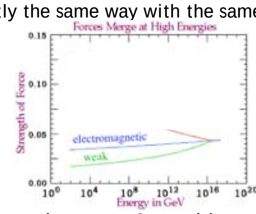
- The Z^o and photon interactions are so similar that they are very difficult to distinguish experimentally.
- One of the ideas behind the Standard Model is that particles physics should follow regular and explainable patterns or symmetries.
- A pattern that would account for two changed weak force carriers also called for a neutral particle: The Z^o a neutral particle much like the photon.
- The Z^o was predicted by the Standard Model, and then found experimentally.

Symmetries in the SM

- The standard model is based on **symmetries**, but they are a little subtle.
- Similarities between photon and Z^o interactions point to a common source.
- Electroweak force with two charges
  - This is ('flavor charge')x('electric like charge')
- This results in four exchange bosons.
  - W^+, Z^o, W^- for flavor charge
  - γ for electric like charge

Symmetry breaking

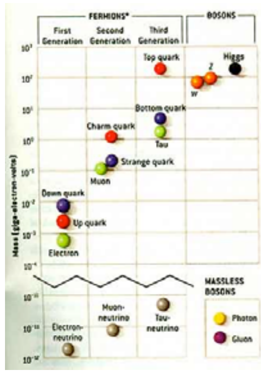
- The standard model says that at high energies, this **symmetry** is apparent
  - We see a single electroweak interaction.
  - Z^o and γ interact exactly the same way with the same strength.
- At low energies the **symmetry** is **broken**
  - We see distinct electromagnetic and weak interactions



- However needs one more element. Something to give the W and Z mass

Mass

- Here's the experimental masses of SM particles.
- Original SM gives zero mass for all particles.
- But can give particles mass by coupling to a new field, the Higgs field.
- Higgs boson is the (unobserved) quanta of the Higgs field.

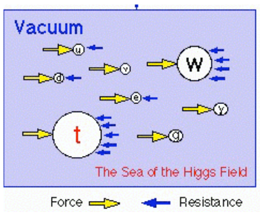


What is mass?

- Think of inertial mass:
  - inertial mass is a particle's resistance to changes in velocity.
- When you apply the same force to particles, the smaller the mass, the larger the acceleration.
- What is the origin of mass?

Mass in the SM

- In the standard model (SM), particles have mass because they interact with something that pervades the universe.



This something is the Higgs field

Particles 'hit' the Higgs field when you try to accelerate them

Mass =
(chance of hit) x (Higgs density)

Coupling constant

Mass and the Higgs field

Imagine a party in a room packed full of people.

Now a popular person enters the room, attracting a cluster of hangers-on that impede her motion

she has become more massive

The Higgs boson

The Higgs boson is a quantum excitation of the Higgs field.

In analogy, suppose an interesting rumor is shouted in thru the door.

The people get quite excited.

They cluster to pass on the rumor, and the cluster propagates thru the room.

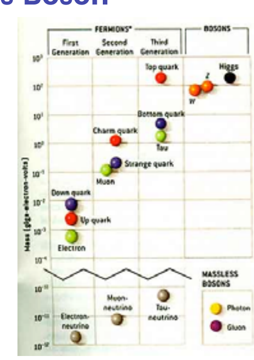
Looks very similar to the popular/massive person who entered the room

Good way to think of other quantum excitations. All the other force carriers

The Higgs Boson

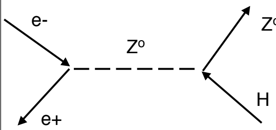
How much mass do you thing the Higgs Boson has

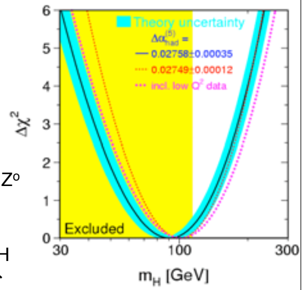
A. No mass
B. Light like an up or down quark
C. Very massive like a top quark



How can we 'see' the Higgs?

- The Higgs boson needs to be created in order to see it. $E = mc^2$
- Not found yet
- $m_H > 114\text{GeV}$
- $m_H < 186\text{GeV}$

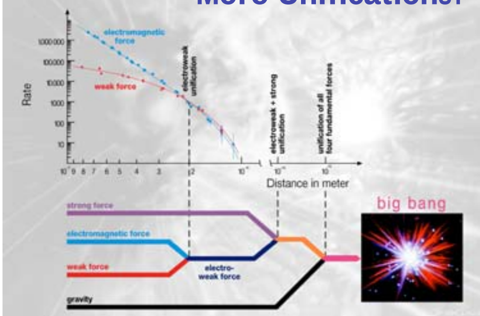




Grand Unified Theories

- What do we really need to unify particle physics?
- Maxwell unified the electric and magnetic interactions into electromagnetic (EM)
- The standard model unified the EM and weak interactions into the electroweak interaction
- Start with the strong force.
- What kind of theory is needed to unify this?

More Unifications?



Not all that easy

"Putting a box around it, I'm afraid, does not make it a unified theory."

Grand Unified Theories

- Flavor changing interactions in quarks (e.g. changing a top quark to a bottom quark by emitting a W^+) suggest that quarks can be viewed as different 'orientations' of the same object.
- Have found the same thing for leptons.
- But maybe there should be a lepto-quark field?
  - Quarks could turn into leptons, leptons into quarks
  - All matter particles would be different 'orientations' of the same fundamental object.
- If we unify leptons and quarks then weak and strong forces may be shown to be two aspects of one force.

The price of unification

- When the SM unified EM and weak interactions, we ended with more force-carrying bosons (e.g. the Z^o)
- This is because our fundamental 'particle' increased in complexity
  - e.g. from an electron to an electron-neutrino pair
- If our 'particle' now encompasses both leptons and quarks, the interaction also becomes more complex.
- In one particular GUT, we get 24 exchange bosons (W^+,W^-,Z^0, photon, 8 gluons, and 12 **new** ones)

Summary

- Details of weak interaction suggest that
  - Different quarks and diff. leptons are diff. 'orientations' of the same particle.
  - Weak and EM interactions are diff. parts the 'electroweak' force.
- Mass
  - Particles get mass by interacting with Higgs field
  - Higgs boson is an excitation of the Higgs field
- Grand Unified Theories (GUTs)
  - Will 'combine' letptons and quarks
  - Unify strong and electroweak interactions
- What's beyond the Standard Model.