From Last Time…

- Particles are quanta of a quantum field
  - Represent excitations of the associated field
  - Particles can appear and disappear
- Particles interact by exchanging *other* particles
  - Electrons interact by exchanging photons
    - This is the Coulomb interaction
    - Electrons are excitations of the electron field
    - Photons are excitations of the photon field
- *Today*

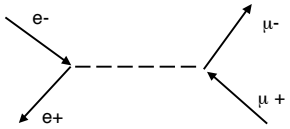
  More particles!

Essay due Friday

Something unexpected

- Raise the momentum and the electrons and see what we can make.
- Might expect that we make a quark and an antiquark. The particles that make of the proton.
  - Guess that they are 1/3 the mass of the proton 333MeV

μ, Muon mass: 100MeV/c^2, electron mass 0.5 MeV/c^2

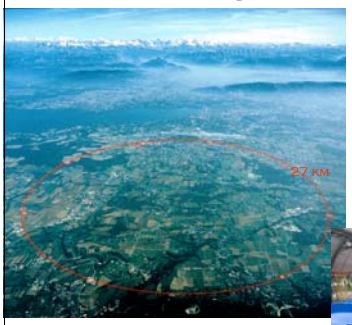


Instead we get a muon, acts like a heavy version of the electron

Accelerators

- What else can we make with more energy?
- Electrostatic accelerator: Potential difference V accelerate electrons to 1 MeV
- Linear Accelerator: Cavities that make EM waves particle surf the waves - SLAC 50 GeV electrons
- Cyclic Accelerator: Circular design allows particles to be accelerated by cavities again and again
  - LEP 115 GeV electrons
  - Tevatron 1 TeV protons
  - LHC 7 TeV protons(starts next year)

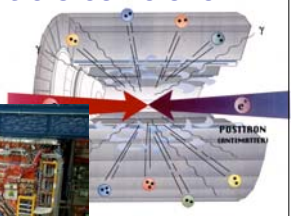
CERN (Switzerland)

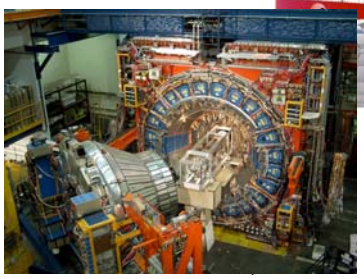


- CERN, Geneva Switzerland
- LHC Cyclic accelerator
- 27km, 14TeV 7+7=14

Measuring particle collisions

Detectors are required to determine the results of the collisions.





- CDF: Collider Detector Facility at Fermilab

Fundamental Particles

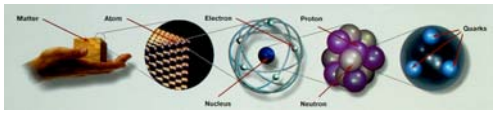
In the Standard Model the basic building blocks are said to be 'fundamental' or not more up of constituent parts.

Which particle isn't 'fundamental':

A. electron
B. muon
C. photon
D. proton

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, photons…

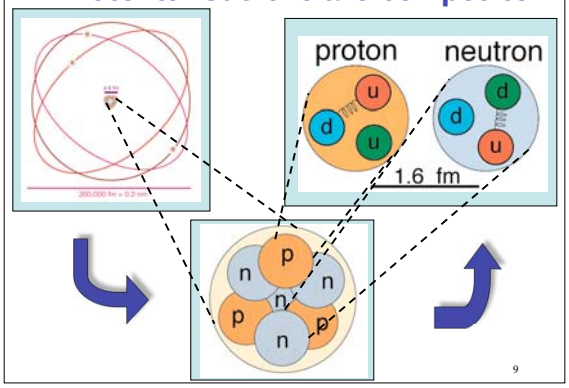
Neutrino

- Neutrino was first detected in 1956
- The neutrino has
  - Zero charge, spin 1/2, *almost* zero mass
- Electron has
  - Charge -e, spin 1/2, mass 0.5 Mev/c^2
- Electron and neutrino generically called leptons

Fred Reines, Clyde Cowan, at the Hanford nuclear reactor

Seen before in the weak interaction.

Protons/Neutrons are composite



Protons, neutrons, and quarks

- Protons and neutrons are made up of
  - 'up' quarks and 'down' quarks

	Charge	*Spin*	*Mass* (MeV/c^2)
Up	+(2/3)*e*	1/2	3
Down	-(1/3)*e*	1/2	6

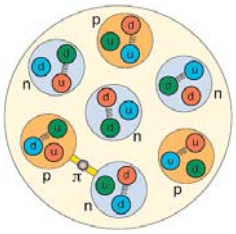
Question

A neutron is a composite particle consisting of three quarks (up=charge +2/3e, and down = charge -1/3e). Which is the structure of the neutron.

	Total charge:
A. up, up, up	+2e
B. up, up, down	+e
C. up, down, down	0

Neutron has zero total charge

Protons & Neutrons



To make a proton:
We bind **2 up quarks** of **Q = +2/3** and **1 down quark** of **Q = -1/3**.
The total charge is
2/3 + 2/3 + (-1/3) = +1 !

To make a neutron:
We bind **2 down quarks of Q= -1/3** with **1 up quark of Q = +2/3** to get:
(-1/3) + (-1/3) + (2/3) = 0 !

Hierarchy of structure

$R \sim 10^{-15}$ m (strong)
protons and neutrons are made from quarks

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

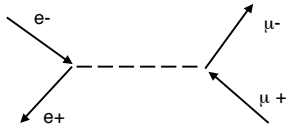
$R \sim 10^{-10}$ m (electromagnetic)
Atoms are made from protons, neutrons, and electrons

$R > 10^{6}$ m (gravitational)
We'll talk about the rest of the universe later

What about the muon?

- The muon found early on.
  - Heavy version of the electron.
- Otherwise would have been fairly simple!

μ, Muon mass: 100MeV/c^2, electron mass 0.5 MeV/c^2



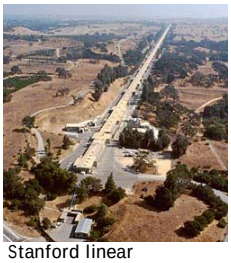
More particles

- In 1975, the tau lepton was discovered at SLAC.(Nobel prize, 1995)

Just like the electron and muon, but 3500 times heavier than the electron

  - Same charge, same spin, but different mass.
- Made this particle by creating more energy.

Both the muon and tau have
Muon-neutrino
Tau-neutrino
(detected in 2000)



Stanford linear accelerator center (SLAC)

The particle garden

- Particle physics at this point has settled on a countable number of 'fundamental particles'.
- The bad news - there are:
  - **(6 leptons +6 quarks)+ (4 electroweak bosons +8 gluons +1 graviton) =25** fundamental particles, not counting antiparticles!
- The good news:
  - These are not just random, but have some relationships that let us understand the ideas without thinking immediately about all the particles.

Three electron-like particles

	Charge	*Spin*	*Mass* (MeV/c^2)
Electron	*-e*	1/2	0.5
Muon	*-e*	1/2	106
Tau	*-e*	1/2	1,777

These are referred to as three 'generations' of particles.

Difference between them is only **mass**

Three neutrinos

	Charge	*Spin*	*Mass* (MeV/c^2)
Electron-neutrino	*0*	1/2	~0
Muon-neutrino	*0*	1/2	~0
Tau-neutrino	*0*	1/2	~0

These are referred to as three 'generations' of particles.

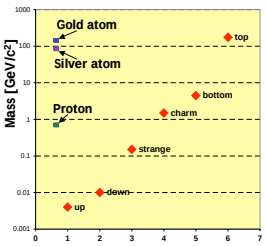
Difference between them is only **mass**

Six quarks

	Charge	Spin	Mass (MeV/c^2)
Up	+(2/3)*e*	1/2	3
Down	-(1/3)*e*	1/2	6
Top	+(2/3)*e*	1/2	1,300
Bottom	-(1/3)*e*	1/2	100
Charmed	+(2/3)*e*	1/2	175,000
Strange	-(1/3)*e*	1/2	4,300

Quarks: Heavy, Heavier, Heaviest

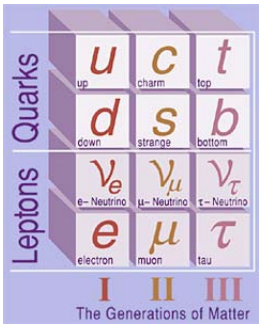
- 6 different kinds of quarks.
- Matter is composed mainly of **up quarks** and **down quarks bound in the nuclei of atoms**.
- Masses vary dramatically (from ~0.005 to 175 [GeV/c^2])
- Heavier quarks are unstable, rapidly decay to lighter quarks



Example: t → b (~10^{-23} [s])
b → c (~10^{-12} [s])
c → s (~10^{-12} [s])
s→u (~10^{-7}-10^{-10} [s])

More on quark decays later…

Three 'generations' of particles



- Three generations differentiated primarily by mass (energy).
- First generation
  - One pair of leptons, one pair of quarks
- Leptons:
  - Electron, electron-neutrino.
- Quarks: Up, down.

All have spin 1/2

The generations of 'matter particles'

Light

Heavier

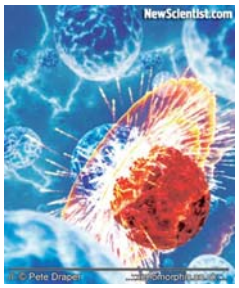
Heaviest

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	<1×10^{-8}	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	−1	s strange	0.1	−1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	−1	b bottom	4.3	−1/3

Antiparticles

- Each of these has an antiparticle, different only by charge.
- Electron antiparticle = positron
- Muon antiparticle = anti-muon
- Tau antiparticle = anti-tau

Matter and anti-matter can annihilate creating energy

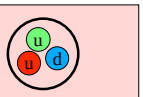


Making more composite particles

- The forces which hold the protons and neutrons together in the nucleus are **VERY strong**.
  - They interact via the **STRONG FORCE**.
- Protons and neutrons are among a class of particles called "**hadrons**" (*Greek for strong*).
- **Particles made of quarks.**
- **Baryons are hadrons** which contain **3 quarks** (no anti-quarks).
- **Anti-baryons are hadrons** which contain **3 anti-quarks** (no quarks).

Use up and down quarks

Quark	up	down	strange
Charge Q	+2/3	-1/3	-1/3
Mass	~5 [MeV/c^2]	~10 [MeV/c^2]	~200 [MeV/c^2]
	u u u	d d d	s s s



Proton
Q = +1
M=938 MeV/c^2

Neutron
Q = 0
M=940 MeV/c^2

Most of the mass is in the binding energy.

Are there baryons other than protons and neutrons?

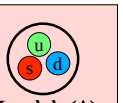
Other quarks can combine to form other baryons.
For example:

This combination is called a Lambda baryon, or Λ^0 for short
Charge 0:
(2/3) + (-1/3) + (-1/3) = 0

More Baryons

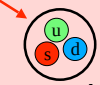
Quark	up	down	strange
Q	+2/3	-1/3	-1/3
Mass	~5 [MeV/c^2]	~10 [MeV/c^2]	~200 [MeV/c^2]
	u u u	d d d	s s s

Excited state - Higher energy/mass



Lambda (Λ)
Q = 0
M=1116 MeV/c^2

Sigma (Σ^+)
Q = +1
M=1189 MeV/c^2



Sigma (Σ^0)
Q = 0
M=1192 MeV/c^2

Sigma (Σ^-)
Q = -1
M=1197 MeV/c^2

Another baryon:

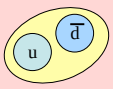
What's this baryon's electric charge?

Delta baryon, or Δ^{++} for short.
Charge: +2
(2/3) + (2/3) + (2/3) = +2 !

A. 0
B. +1
C. +2

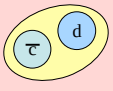
Mesons

- They are formed when a **quark** and an **anti-quark** "bind" together.
- So far we've only seen 3 quark combinations. There are also 2 quark combinations.
- The hadrons: 2 quarks, meson and 3 quarks, baryon.



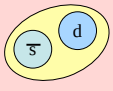
What's the charge of this particle?

Q=+1, and it's called a π^+



What's the charge of this particle?

Q= -1, and this charm meson is called a D^-



What's the charge of this particle?

Q= 0, this strange meson is called a K^0

Leptons and quarks: what's the difference?

- One important difference is how they interact.
- We said the Coulomb interaction is between particles with electrical charge.
- Understood by exchanging photons.
- The other interactions:
  - Weak
  - Strong
  - Gravitational
- Particles understood/defined by how they interact

Electromagnetic Force

In the Standard Model particles are often classified by what forces they interact via.

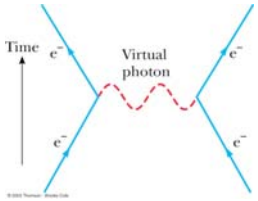
Which of these particle does not interact with the electromagnetic force:

A. electron
B. muon
C. photon
D. quark

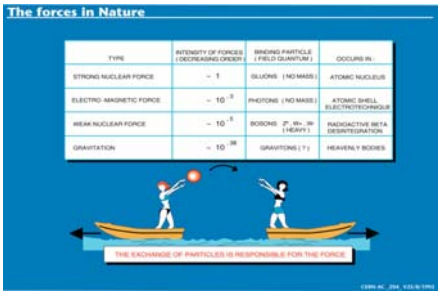
Interactions between particles

- The modern view of forces is in terms of particle exchange.
- These are 'virtual' particles of the fields created by the particle charges.

This shows Coulomb repulsion between two electrons. It is described as the exchange of a photon.



Four Gauge forces



Exchange bosons

- Each interaction has one or more associated particles that **mediate** the interaction.
- The exchange particles are associated with the known interactions

Interaction	*Mediating particle(s)*	*Number*
Electro-magnetic	photon	(1)
Weak	W^+, W^- and Z^o	(3)
Strong	gluons	(8)
Gravity	graviton	(1)

- These all have integer spins, hence are bosons

Bosons

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0