2. What is a Hadron?

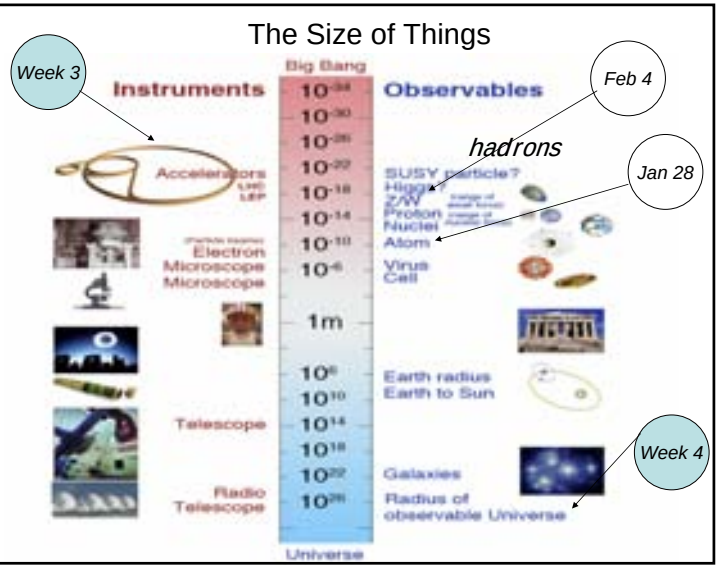
February 4, 2010

The Standard Model of Particle Physics
&
Fundamental Forces
(- Gravity)

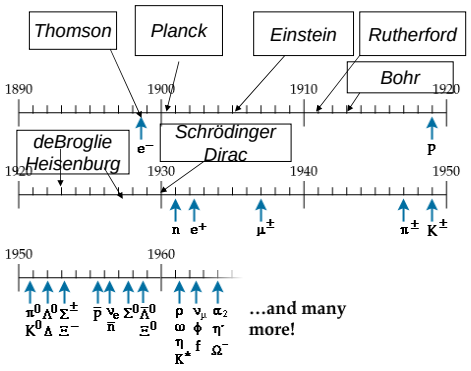
What is a Hadron: Topics

1. Blitzkrieg Review of last week's attempted summary of ~100 years of Forefront Physics!
2. Bringing Order out of the Chaos
   - Matter and Anti-matter
   - Forces on matter
     - The Electromagnetic and Weak Force(s) that act(s) on Hadrons
     - The Strong Force that acts on Hadrons
     - A word on decay
     - The Higgs Mechanism for creating Mass out of Energy

Blitzkrieg Review
of last week summary of
~100 years of Forefront Physics!



The atom, as it is progressively investigated, turns out to be increasingly divorced from our everyday experience.



A new way to view force

Forceful Animation

Yukawa postulated that mesons, messenger particles, carried “force” between protons and neutrons.

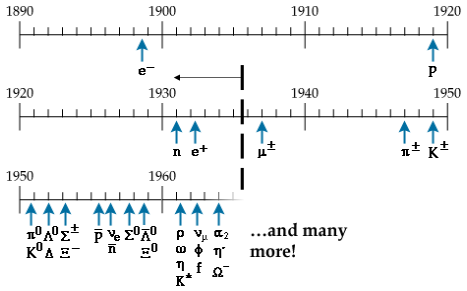
That is, the atomic world is screwy.

Richard Feynman:

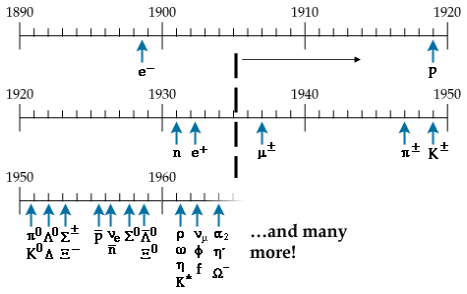
“ . . .I think I can safely say that nobody understands Quantum Mechanics.”

p. 129, the Character of Physical Law, 1986, MIT Press, 13th Printing

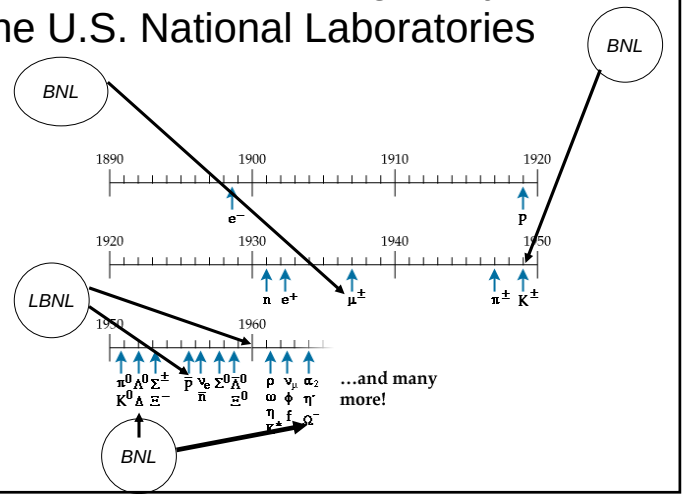
Our experience of the atomic world is stage right of the dashed line.



We are will be looking today at stage left of the dashed line.



Most of which is brought to you c/o the U.S. National Laboratories



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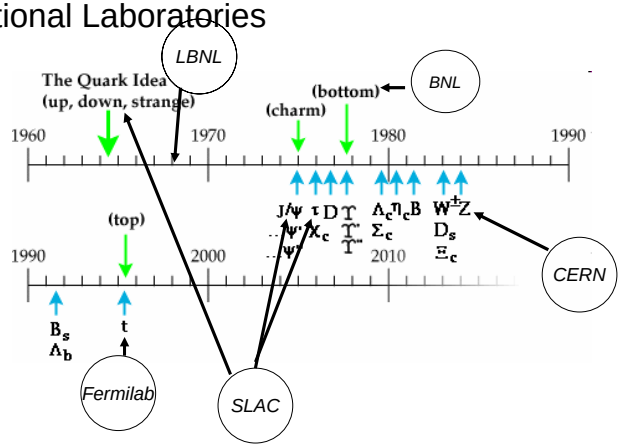


On the Shoulder of Giants: *Historical Perspective*

The Driving Question of Modern Physics: How does the atom work?

- 1948 Feynman, Tomonaga & Schwinger combine QM and Special Relativity in Quantum Electrodynamics or QED (NPP65)
- 1964 Quarks proposed as fundamental (Gell-Mann NP69)
- 1983 Experimental verification of QED (Rubia, van der Meer, NPP84)
- 1994 Existence of Top Quark confirmed
- 1998 Neutrinos found to have nonzero mass

theory

experimental verification

Great Intellectual Achievement! → *The Standard Model of Particle Physics*

To bring order out of the Chaos, Physicists created:

The Standard Model of Particle Physics

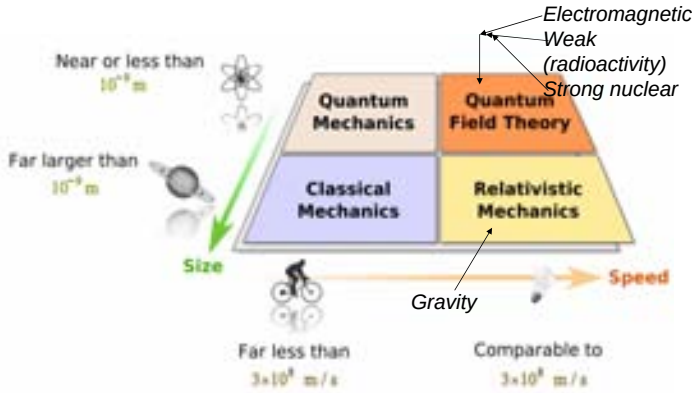
&

Fundamental Forces

(- Gravity)

No accounting for Gravity in a Quantum (Lumpy or Particle) Theory

What about relativity?



The Standard Model

Part 1.

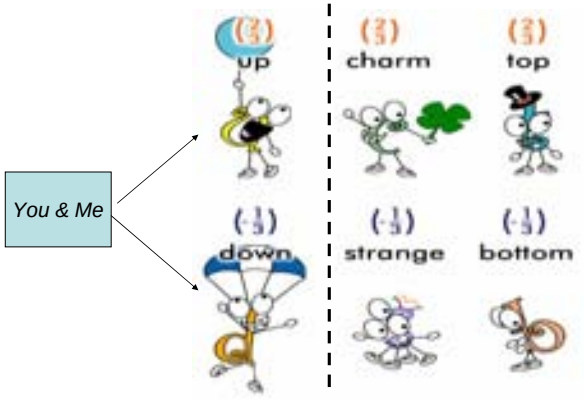
Fundamental “matter” particles

Standard Model

Matter particles		
QUARKS	up	u
	down	d
	charm	c
	strange	s
	top	t
	bottom	b
LEPTONS	electron neutrino	ν_e
	electron	e
	muon neutrino	ν_μ
	muon	μ
	tau neutrino	ν_τ
	tau	τ

you & me

Why the names?

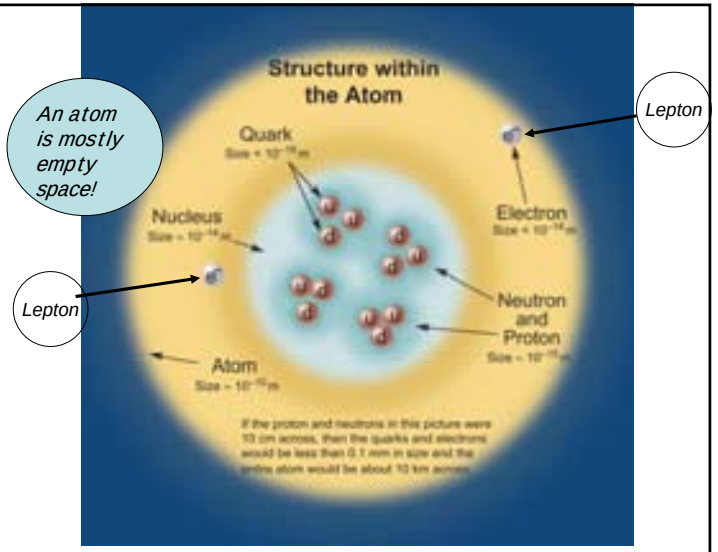


Standard Model

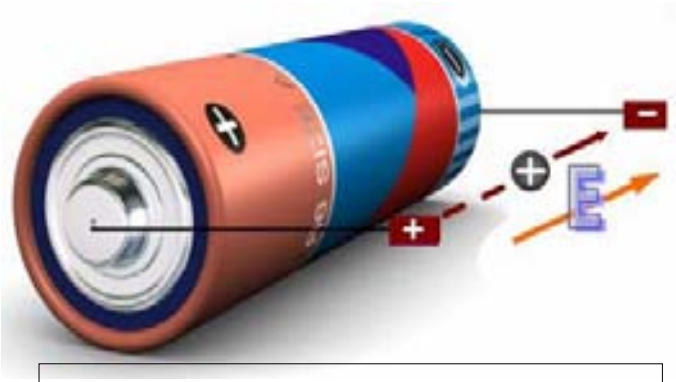
Electric Charge

Generation

~~FAMILY~~	QUARKS		LEPTONS	
1 (*You & Me*)	u +2/3	d -1/3	ν_e 0	e -1
2	c +2/3	s -1/3	ν_μ 0	μ -1
3	t +2/3	b -1/3	ν_τ 0	τ -1



Mass is measured as Energy!



1 eV_= 1.602 x 10 $^{-19}$ joules (or watts-sec). 100 joules will power A 100 watt light bulb for one second.

Everyday eV Energies

Room temperature thermal energy of a molecule.... .....0.04 eV
Visible light photons.....1.5-3.5 eV
Energy for the dissociation of NaCl into Na+ and Cl- ions:.....4.2 eV
Ionization energy of atomic hydrogen .....13.6 eV

~ Energy of an electron striking a TV screen.....20 keV
High energy diagnostic medical x-ray photons .....200 keV

Typical energies from nuclear decay:
(1) gamma..... .....0-3 MeV
(2) beta.....0-3 MeV
(3) alpha.....2-10 MeV

Cosmic ray energies .....1 MeV - 1000 TeV

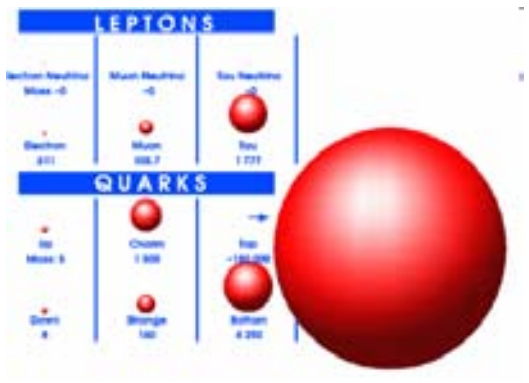
Elementary particles with masses expressed in electron volts

You & me →

QUARKS		LEPTONS	
u	d	ν_e	e
2-8 MeV	5-15 MeV	< 8,0 eV	511 keV
c	s	ν_μ	μ
1,0-1,6 GeV	100-300 MeV	<270 keV	106 MeV
t	b	ν_τ	τ
170-180 GeV	4,1-4,6 GeV	<35 MeV	1,78 GeV
VECTOR BOSONS			
W^+	W^-	Z^0	
80 GeV	80 GeV	91 GeV	

Why the Size?

In MeV



What is a Hadron?

The stuff of quarks and anti-quarks.

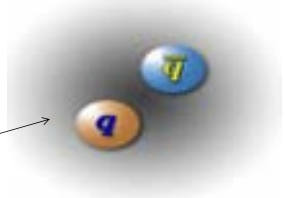
Recall that quarks (and anti-quarks) are Massive (on the atomic scale)

Hadron comes from the Greek, *hadros,* meaning stout, thick, strong, heavy

Hadrons: heavy, strong stuff
The stuff of Quarks and Anti-Quarks

3 quarks make baryons (neutrons, protons, etc)

2 quarks (quark + anti-quark) make a meson



Hadrons: Let's get real

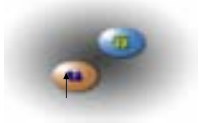
Proton

+2/3 +2/3 – 1/3 = +1

-1/3 -/13 + 2/3 = 0

Neutron

Π-Meson pion



Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

All Hadrons (baryons, i.e. 3 quark combinations) have integer electric charge

Δ^{++} uuu *+2/3 +2/3 +2/3 = +6/3 = +2*

Δ^{-} ddd -1/3 -1/3 -1/3 = -3/3 = -1

Λ uds +2/3 -1/3 -1/3 = 0

Ω^{-} sss -1/3 -1/3 -1/3 = -3/3 = -1

Mesons $q\bar{q}$

Mesons are bosonic hadrons

These are a few of the many types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Hadrons – Mesons -- adding up to integer charges

Π^+ u d-bar +2/3 +1/3 = +1

K^- s u-bar -1/3 -2/3 = -1

$\rho+$ u d-bar +2/3 +1/3 = +1

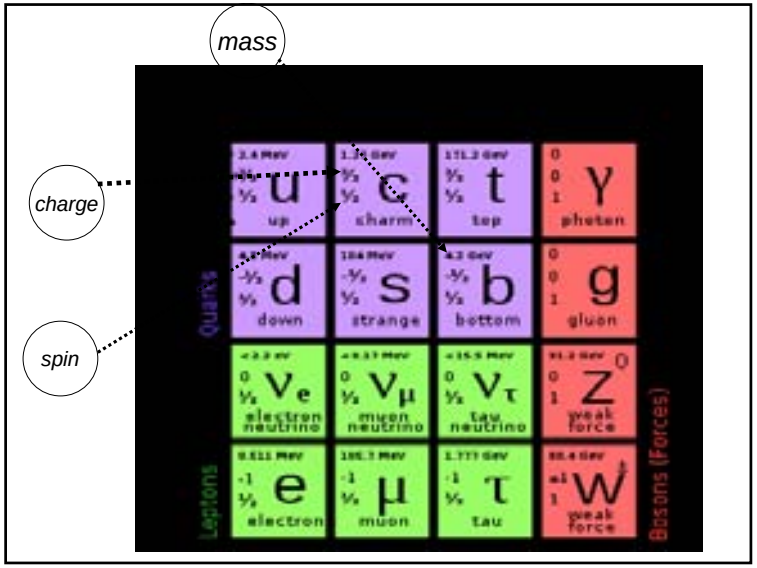
B^0 d b-bar -1/3 +1/3 = 0

η_c c c-bar +2/3 -2/3 = 0

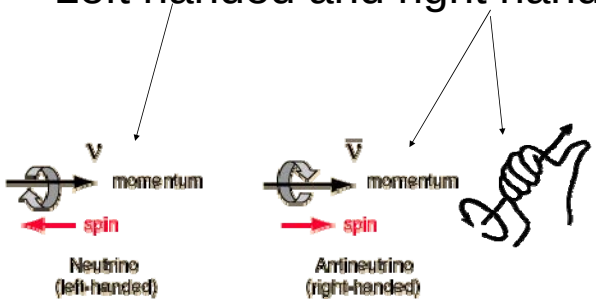
What makes Quarks so different?

- An Expert's Answer
- http://www.fnal.gov/pub/science/questions/particle-world-01.html

Another Property Of Quarks



Left handed and right handed



FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0–0.13)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009–0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04–0.14)\times10^{-9}$	0
τ tau	1.777	−1

Quarks spin =1/2

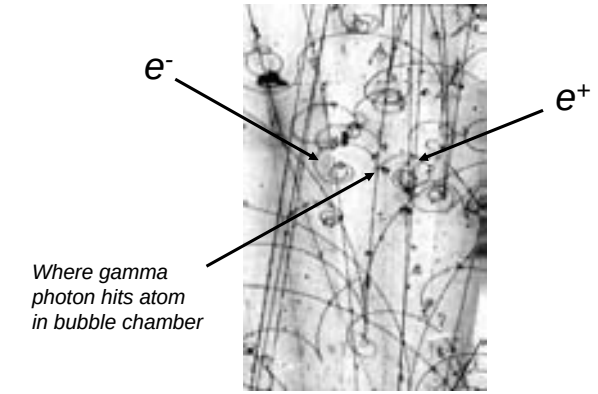
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

What's the matter with Anti-Matter?

Anti-Matter Experimental Evidence

as Seen in a Fermilab Bubble Chamber

Image courtesy of Fermilab



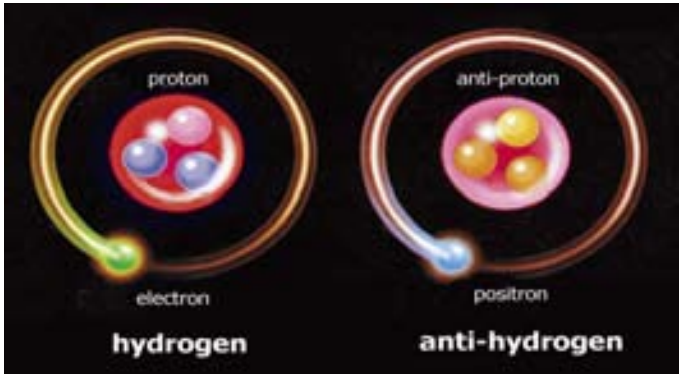
An explanation

Persis Drell on Anti-Matter

(Director, SLAC National Accelerator Laboratory)

- Invited Speaker
- http://www.fnal.gov/pub/science/questions/birth-universe-02.html

Anti-Matter



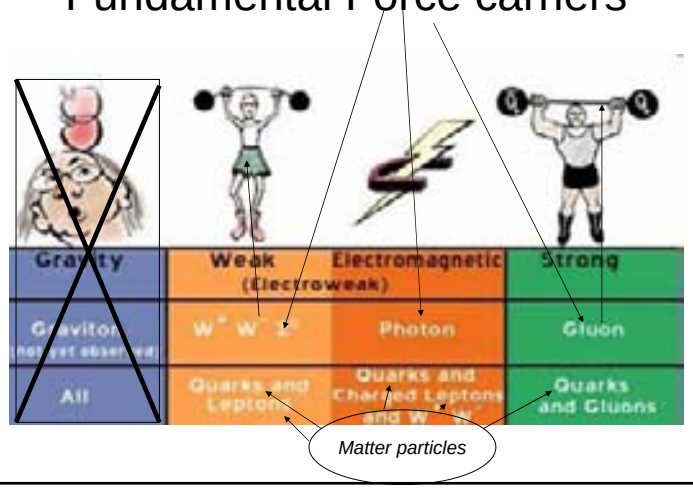
The Standard Model

Part 2.
The Fundamental Forces
(- Gravity)

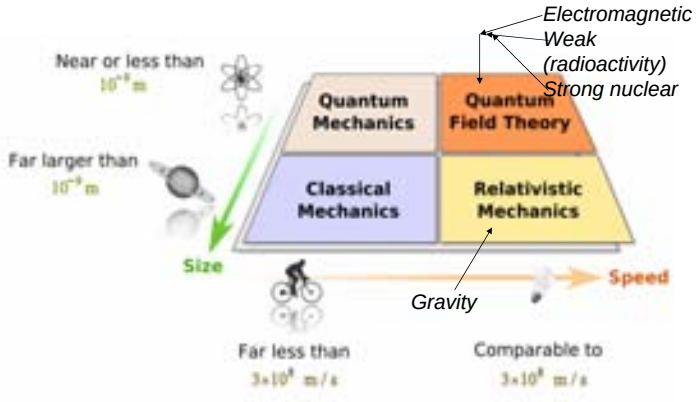
What holds the matter together?

Forces, or Interactions

Fundamental Force carriers



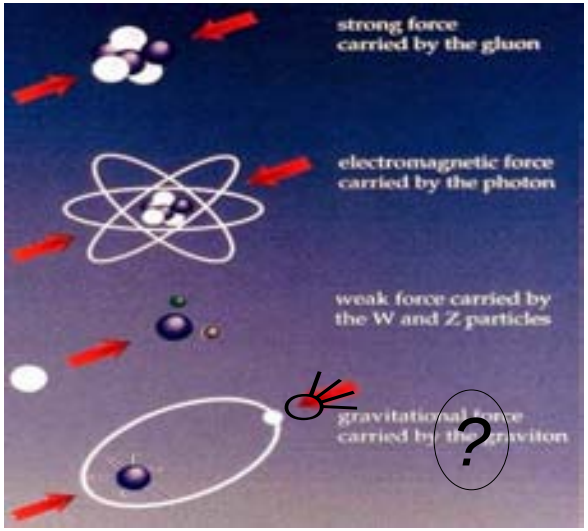
What about Gravity?



Force Mediator/interaction

Forceful Animation

No information can be transmitted faster than the speed of light, according to the Theory of Relativity.



The relative strength & range of the four interactions.

Type	Strength	Range	Mediator
strong	1	10^{-15} m	gluons (8)
electro-magnetic	10^{-2}	∞	photon
weak	10^{-5}	10^{-18} m	W^+, W^-, Z^0
gravity	10^{-38}	∞	graviton

BOSONS

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

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

The Electro Weak Force

Photon

W, Z Bosons

Electromagnetic

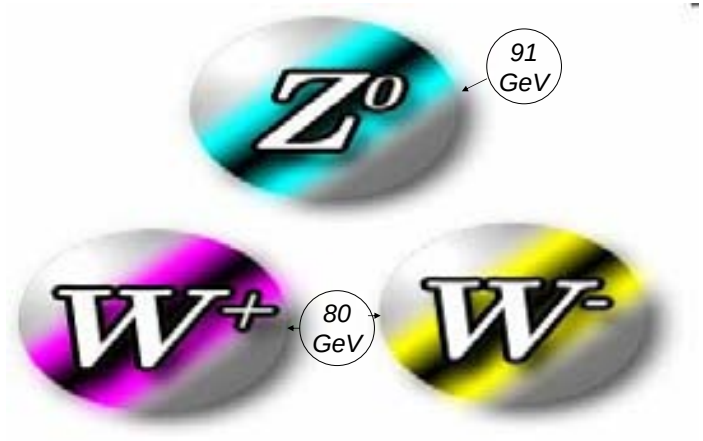
http://hands-on-cern.physto.se/ani/part_fire/intro_eng.swf

- Photon at Work

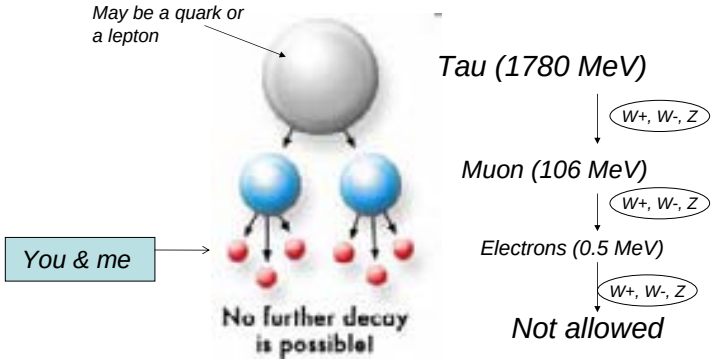
According to the Theory of Relativity, nothing can travel faster than the speed of light, including information & force carriers.

The Weak Force

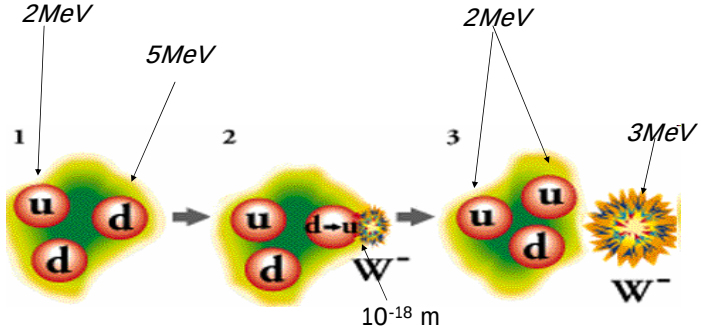
The Weak Force Carriers



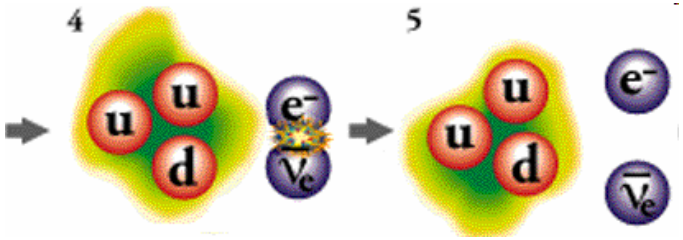
The Weak Interaction controls the decay of fundamental particles.



An example of a weak Interaction: $n \rightarrow p e^- \bar{\nu}_e$



Weak $n \rightarrow p e^- \bar{\nu}_e$



The Weak Interaction acts only on left-handed particles.

The Standard Model

Generation	Quarks, experience the Strong Force				Leptons		
1st (everyday matter)	**Up_L 3 MeV**	**$Down_L$ 7 MeV**	**Up_R 3 MeV**	**$Down_R$ 7 MeV**	**Electron neutrino L ~0**	**$Electron_L$ 0.5 MeV**	**$electron_R$ 0.5 MeV**
2nd	$Charm_L$ 1.2 GeV	$Strange_L$ 120 MeV	$Charm_R$ 1.2 GeV	$Strange_R$ 120 MeV	Muon neutrino L ~0	$muon_L$ 106 MeV	$muon_R$ 106 MeV
3rd	Top_L 174 GeV	$Bottom_L$ 4.3 GeV	Top_R 174 GeV	$Bottom_R$ 4.3 GeV	Tau neutrino L ~0	Tau 1.8 GeV	Tau 1.8 GeV
	Left Handed quarks experience Weak Force				Left handed leptons experience Weak Force		

Mass of Proton ~ 1 GeV = 1,000 MeV
Mass of electron ~ 1 MeV

The Uniqueness of the weak force/interaction

1. The "force" that practices alchemy – i.e. changes particles into other fundamental particles
2. The only "Force" carriers (W+, W-, Z^0) to have mass (80, 91 GeV)
3. The only "Force" carriers to be charged with the Weak Charge.
4. Only one force carrier at a time is involved in an interaction.
5. The affect of W+, W-, Z falls off over a very short distance -- 10^{-18} m – making the interaction improbable.
6. The Weak force/interaction distinguishes from left and right spin.

The Electro Weak Force = Quantum Electro-Dynamics (QED)

On the Shoulder of Giants: *Historical Perspective*

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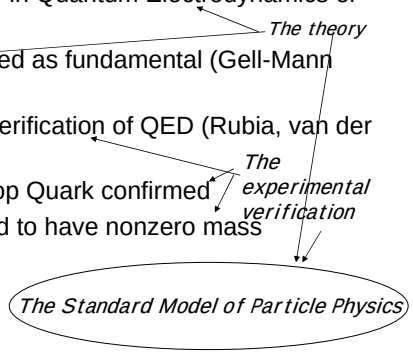
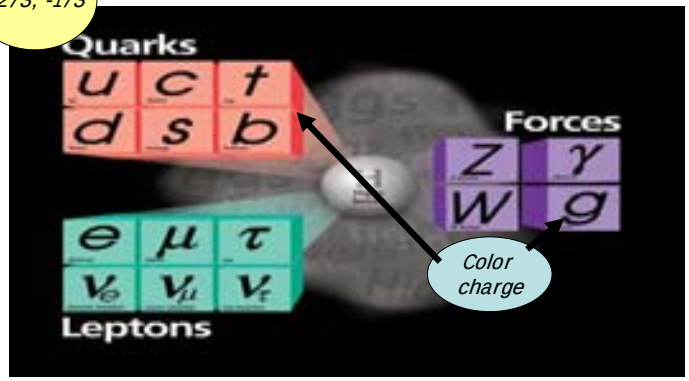


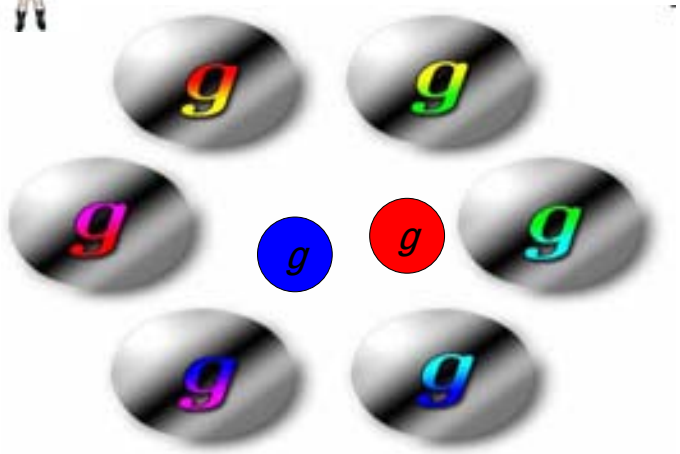
The Strong Force

Quarks carry both electric charge and color charge

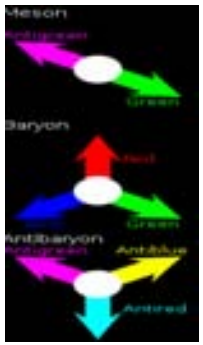
+2/3, -1/3



Strong Force carriers: 8 gluons



Strong carriers interact with Quarks according to their Color Charges

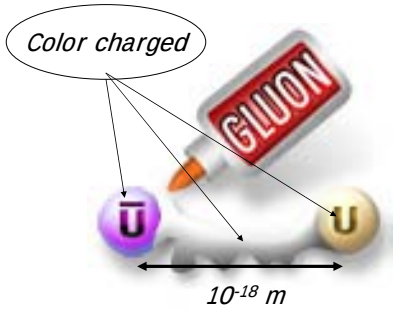


← *qq*

← *qqq*

(q-bar)^3 →

Strong force:



Gluons carry both a color charge and an anti-color charge.

Color Charge is Conserved

Color Transformation

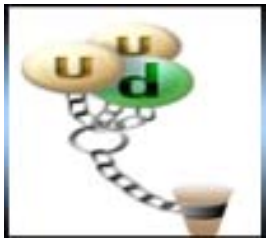
g/g-bar

q➔q

Net color is still red because the blue color of the quark q *cancels the anti-blue color of the gluon* g-bar

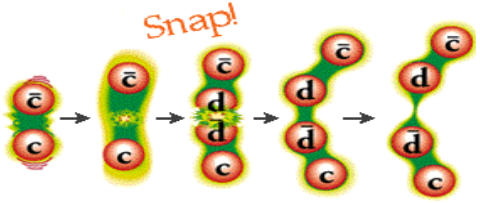
Color charges are only found in Groups

Quarks only come in color neutral combinations.



Cannot be color neutral, so such combinations do not exist

What happens when the color force field is stretched?



New mass is a snap!

But what holds the nucleus together?

Residual Strong Force

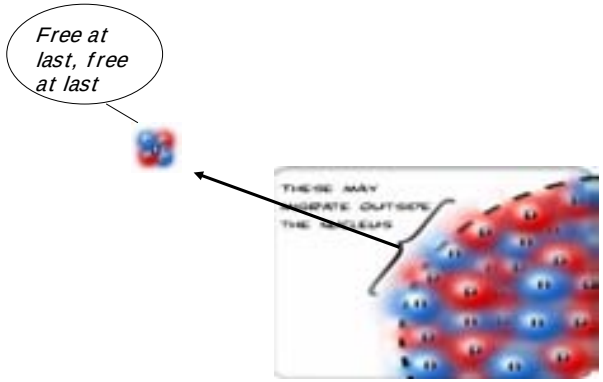
Electric repulsion < strong nuclear force residual

A word on decay

Nuclear & Particle Decays

http://particleadventure.org/decay_intro.html

Nuclear Decay



3 Kinds of Particle Decays: Weak, Electromagnetic & . . .

Weak Decays – transformative

Charm Decay

C ➔ S + W ➔ S + (u, d)

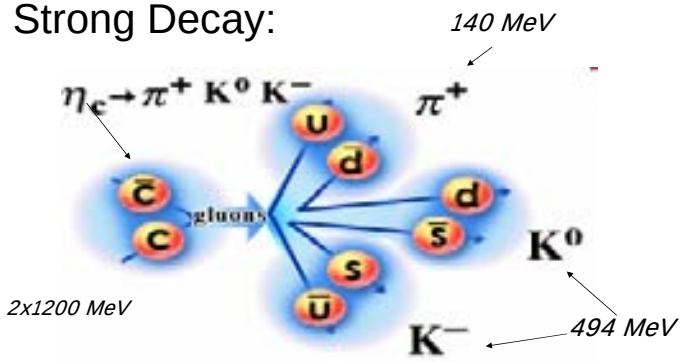
1200 MeV ➔120 MeV + 80 MeV ➔120 MeV + (3+7) MeV

Electromagnetic

π^0 ➔u d-bar ➔ 2 photons (γ)

electromagnetic force carriers

3 Kinds of Particle Decays: Weak, Electromagnetic & . . . Strong Decay:



Summary: Big Questions raised by the Standard Model

Why 3 families of quarks & leptons?

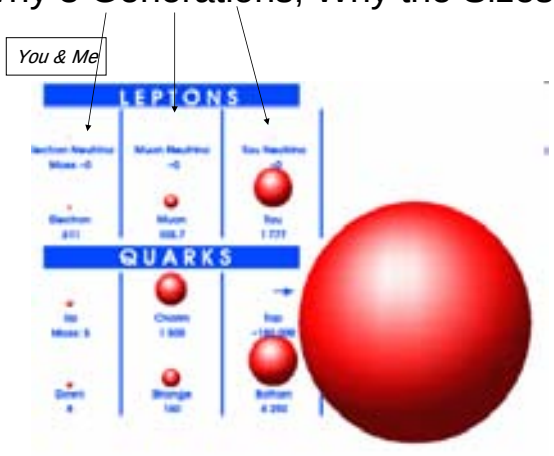
Why the variations in masses of the quarks and leptons?

Why do only “left handed” particles experience the weak force?

Why is there more matter than anti-matter?

Why -- and why so big-- difference in the force strengths of strong, electoweak and gravity?

Why 3 Generations, Why the Sizes?

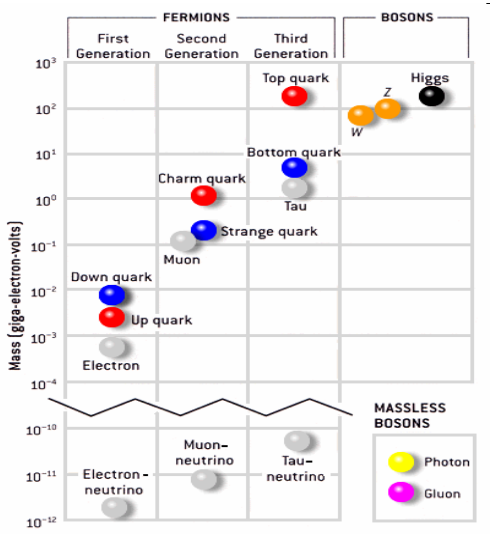


J. Bagger on Unification of Forces

Invited Virtual Speaker

Higgs Mechanism

- How Mass is acquired
  - Higgs Field – the Mechanism
  - Higgs Boson – a force carrying particle



Higgs Mechanism

HiggsMechanism

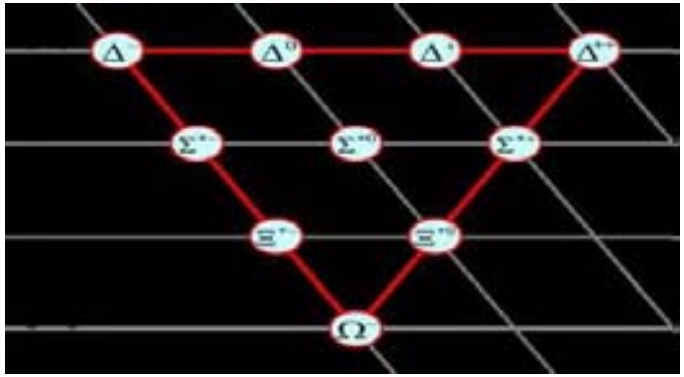
Higgs Mechanism

Higgs Boson

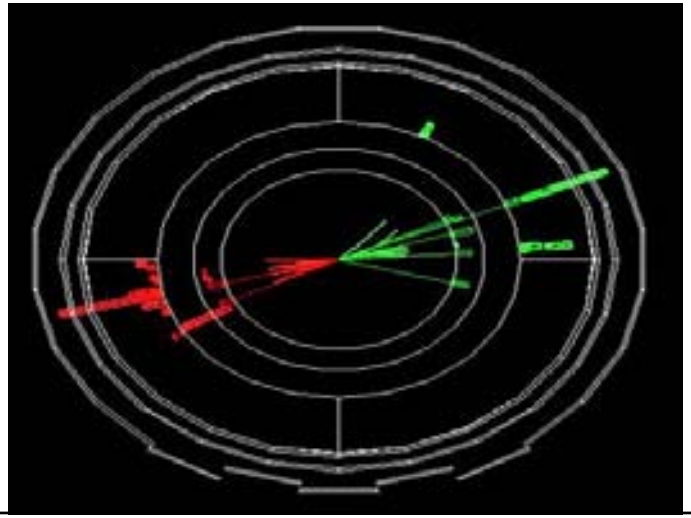
Higgs Boson

BACK UP

Particles in the Particle Zoo

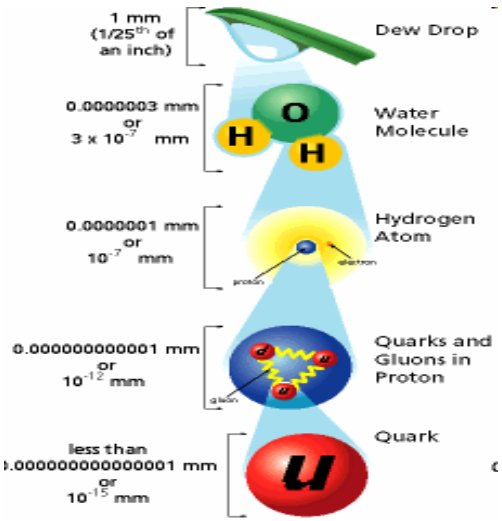


A “Picture” of the Z Boson

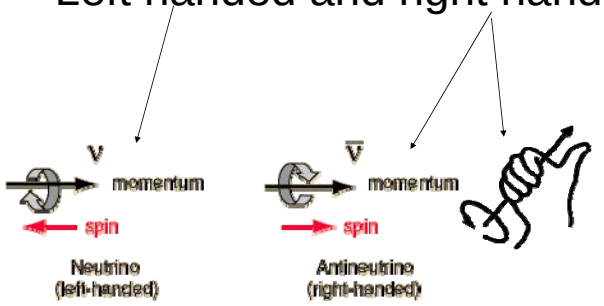


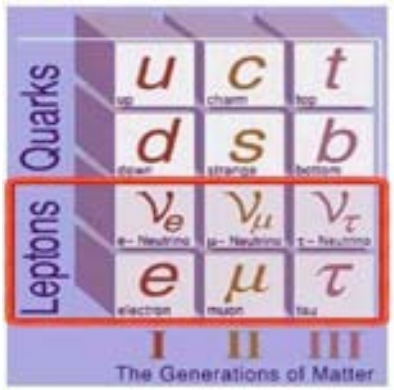
Some other properties:

	muon		muon neutrino		electron		$\bar{e}$ antineutrino
equation:	μ	$\rightarrow$	ν_μ	+	e^-	+	$\bar{\nu}_e$
electron number:	0	=	0	+	1	+	-1
muon number:	1	=	1	+	0	+	0
tau number:	0	=	0	+	0	+	0

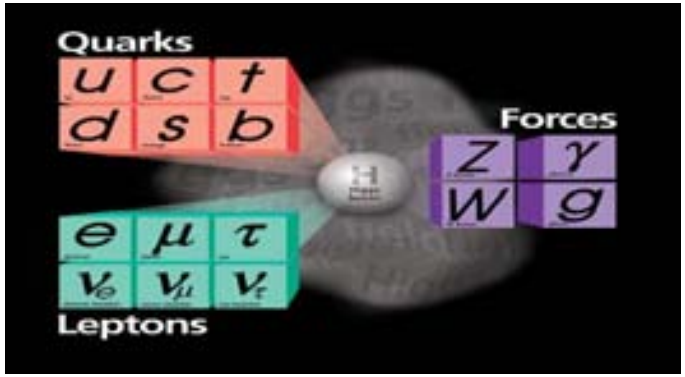


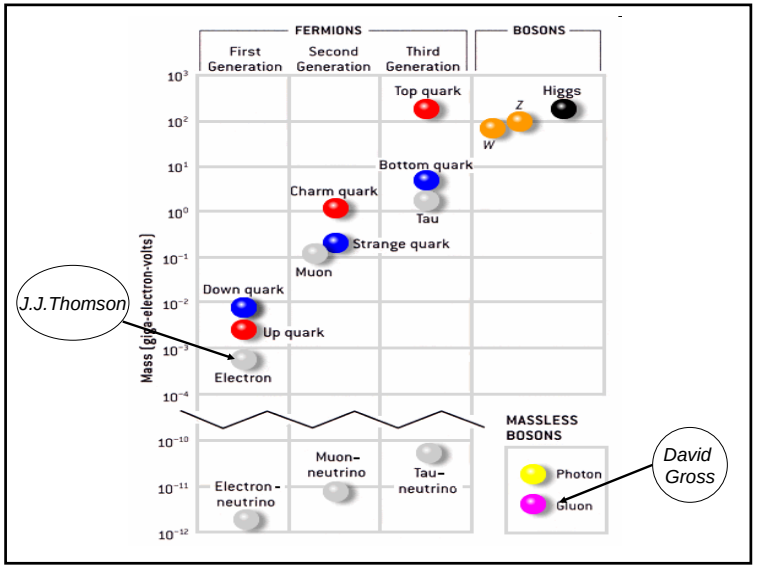
Left handed and right handed

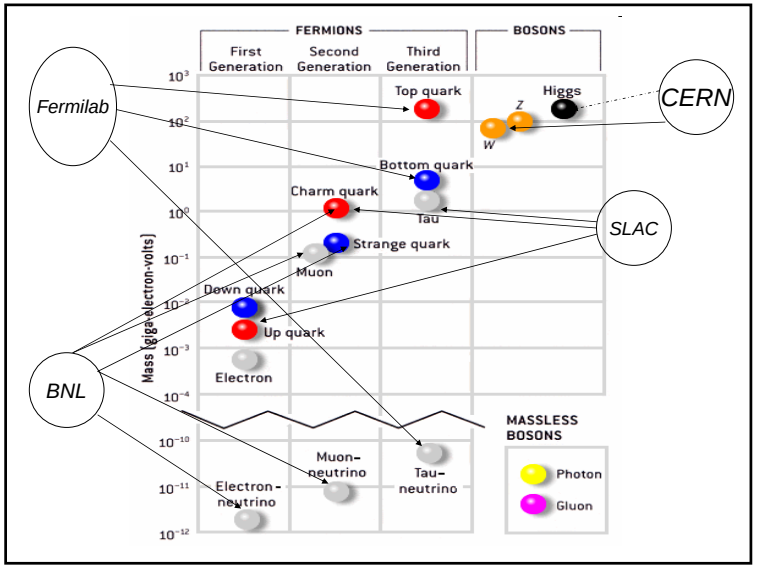


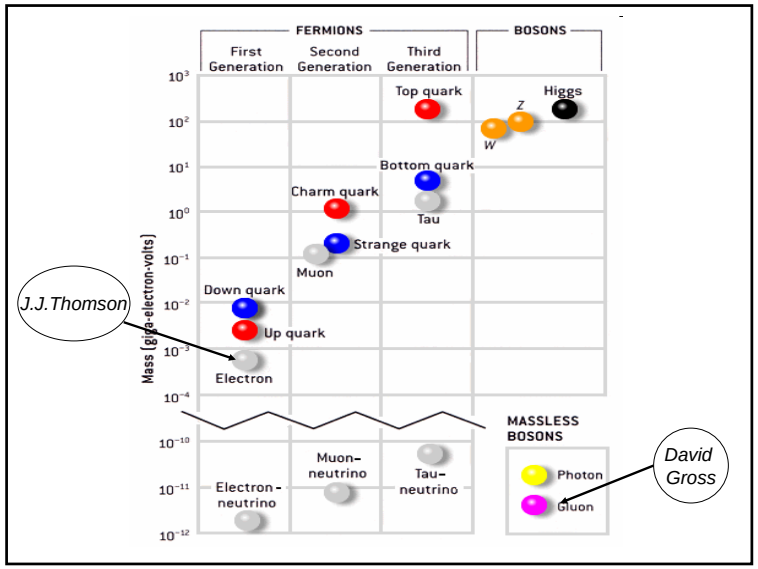


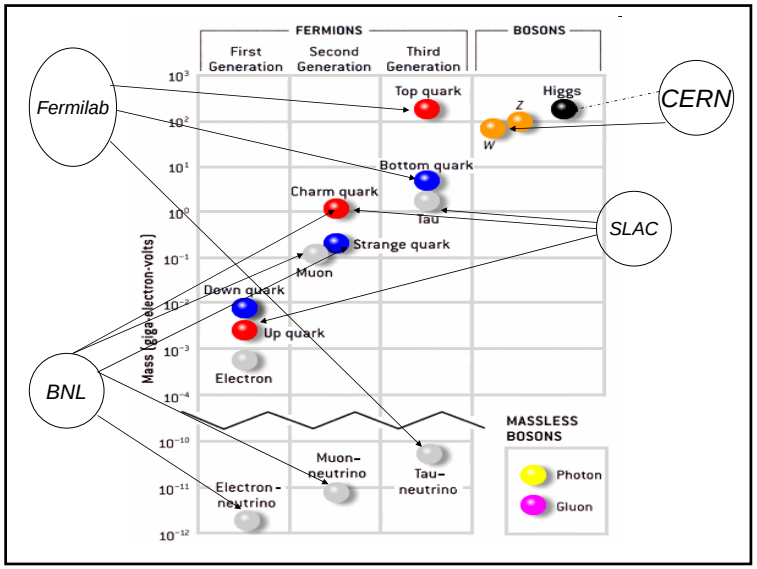
Historic discoveries



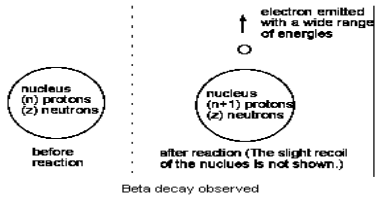








The Neutrino



Beta decay observed

Neutrino Properties	
Mass	Zero or very small
Speed	The speed of light or slightly less
Charge	Zero
Energy	A continuous range of energies
Varieties	Three types of neutrinos, each with an antiparticle