Understanding “The Standard Model”

A Brief History of the Quest to Understand the Universe

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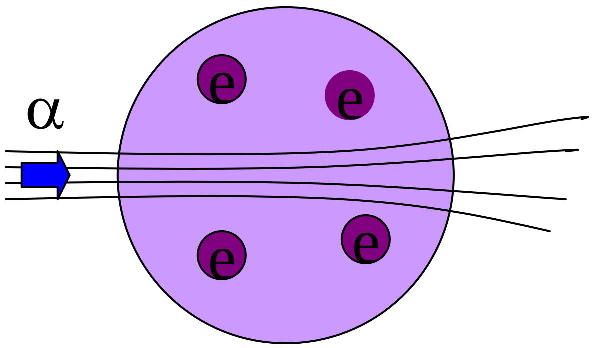
“The Standard Model”
What it is and is not.

- What this is:
  - A list of particles discovered so far, proton, neutrons, etc. composed of strongly bound quarks
  - A unification of the weak and electromagnetic forces
  - Descriptions of the electromagnetic, weak, and strong force in terms of exchanges of fundamental particles
- What this is not:
  - A complete explanation for the universe
  - Unification of the strong and electroweak
  - Gravity
  - Explanation of heavy generations and other phenomena

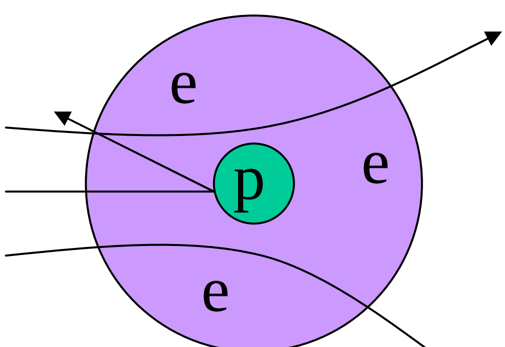
A Brief History of Particles

- 1895 – Radioactive decay discovered(Becquerel and Currie)

- Something was happening to atoms, but what?



- The electron was known
- Popular model of atom was J.J. Thomson's "plum pudding"



- 1911 Ernest Rutherford used alpha particles from polonium to study atoms
- Found a very interesting result: Protons

A Brief History of Particles

- 1914 – Now the model nucleus contains protons and electrons, but there is still some concern
- There are two problems
  - Spin
  - Mass

Spin

- Spin is a property that can be measured like mass or charge
- It is an analogy to a spinning top, but particle spin is just an internal property of the particle
- Generally say Spin is either up or down, indicated by: $\uparrow$ or $\downarrow$
- Spin is additive, canceling up and down

$$\tfrac{1}{2}\uparrow + \tfrac{1}{2}\uparrow = 1\uparrow$$

$$\tfrac{1}{2}\uparrow + \tfrac{1}{2}\uparrow + \tfrac{1}{2}\downarrow = \tfrac{1}{2}\uparrow$$

A Brief History of Particles

Spin

- Why is this a problem?
  - The nitrogen nucleus: 14p + $7e^-$
  - The nucleus has a total spin of 1, which isn't possible with 21 spin ½ particles
  - The was also the problem of:

Mass

- If we treat the mass of the proton as 1, and consider the mass of the electron negligible, atoms should weigh about the same as the number of protons they have.
- Nitrogen doesn't! It weighs around 21! Why?

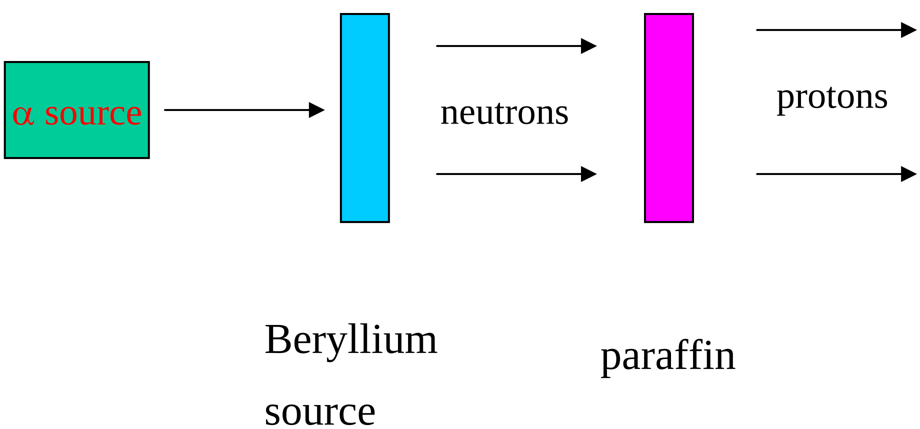
A Brief History of Particles

The Solution

• As early as 1920 scientists suspected there was a neutral object within nuclei

• 1930 the proton-electron models were considered inadequate

•1932 – James Chadwick, an associate of Rutherford, discovered the neutron



A Brief History of Particles

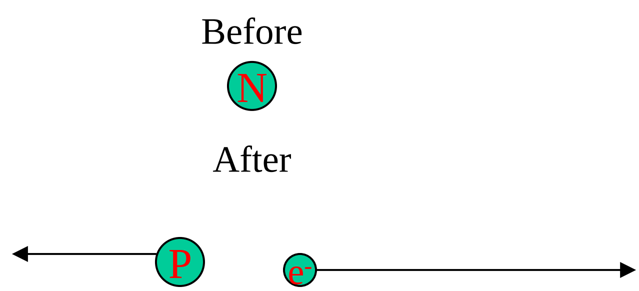
The Three Types of Radiation

- Alpha particles(α)
  - Helium nuclei: 2 protons and 2 neutron
- Gamma radiation(γ)
  - Electromagnetic radiation
  - Caused by excited nuclei releasing energy
- Beta particles(β)
  - Emission of an electron from inside the nucleus
  - Caused by spontaneous neutron decay

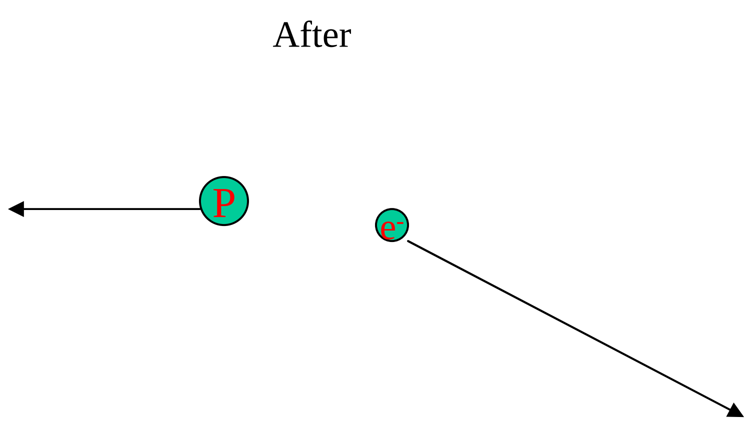
A Brief History of Particles

A Closer look at Beta Decay

- If a neutron decays and emits an electron, by conservation of momentum you expect to see:



- But this was not seen

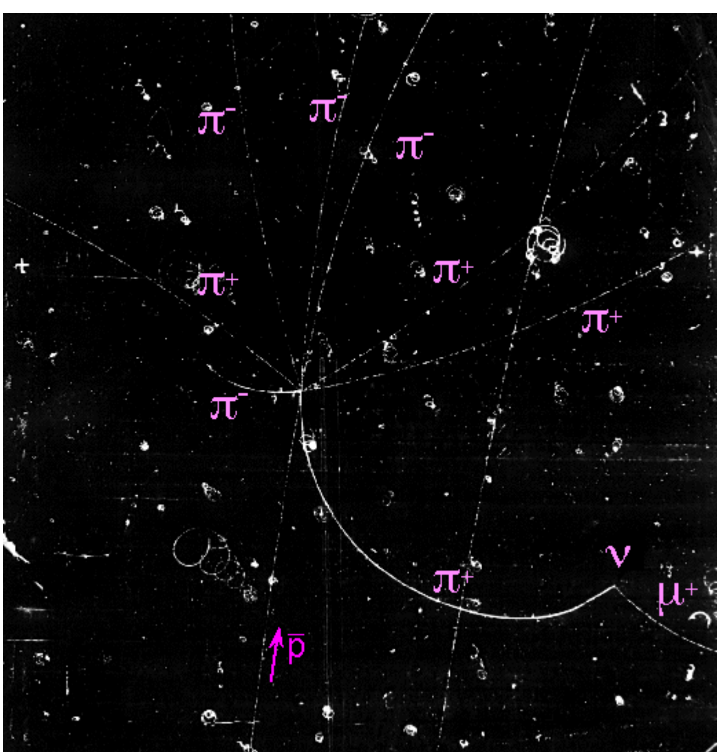


- Something was carrying off the extra momentum, but what?

A Brief History of Particles

The Solution, and then a few more problems

- Rather than scrap the laws of conservation, Wolfgang Pauli proposed the neutrino(ν) with the following characteristics:
  - Little or no mass
  - ½ spin
  - No electric charge
- This would save the laws of conservation, but no one could detect this particle!!



- Finally observed in 1956 using a bubble chamber at the Savannah River Reactor

A Brief History of Particles

Anti-Matter, and A Few More Problems

- 1928 – Paul Dirac
  - Demonstrates that any theory which combines special relativity and quantum theory must contain antiparticles
    - Possess the same spin and mass as the “normal” particle but opposite electric charge
    - The positron was detected in 1932
    - What about the antiproton?
    - How do you tell an antineutron and anti neutrino from there counter part?
- Problems with Quantum Theory and protons and neutrons
- Post WWII SLAC finds that protons are composite, but can’t see of what
- While searching for pions scientists found muons, the bigger cousin of the electron, and predicted its corresponding neutrino
- The also found a whole lot of other things(kaons, lamdas…) called hadrons, where was the expected simplicity of nature?
- Certain decay processes that “should” be possible weren’t occurring, something “strange” was going on

A Brief History of Particles

Quarks!!

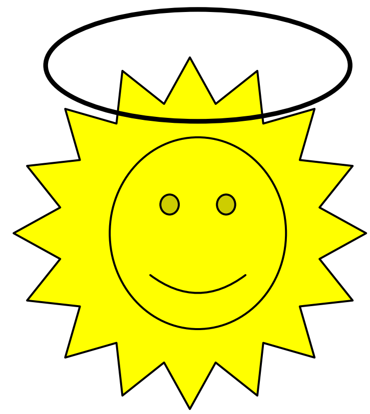
- 1964 – Murray Gell-Mann and George Zweig independently developed the theory of quarks
  - Explained all known hadrons
  - Solved the strange problem
  - Explained the difference between neutral particles and their antiparticles
- Proposed a three quark model, with antiparticles
  - Up, Down, and Strange
  - Called **flavors** by physicists in an analogy to ice-cream
- 1968 – Analysis by Richard Feynman and James Bjorken showed that the upgraded beam at SLAC had seen quarks
- So all is well, right?

A Brief History of Particles

The Not So Complete Picture

- Scientist now have the “standard model”
- Something wasn’t right though, it lacked symmetry
- 4 leptons, but only three quarks
- This led scientists to predict a fourth quark, charm, the partner for strange

u	d		s
ν_e	e^-	ν_μ	μ^-



- 1974 – Brookhaven National Lab and SLAC both discover the charm quark
- Wasn’t in a free state, was bound in a quark meson with its anti-quark called the J/Ψ.

A Brief History of Particles

Completing the Picture

- At that same experiment in 1975 they discovered the tau, the biggest brother of the electron
- A short time later the corresponding neutrino, ν_τ is inferred
- This also begins the quest for the matching quarks, top and bottom.
- 1977 – Bottom Quark Discovered
- 1994 – Top Quark Discovered
- 2000 – Tau Neutrino directly observed

A Brief History of Particles

Completing the Picture

<u>Leptons</u>

- electrons, muons, taus, and associate neutrinos

<u>Quarks</u>

- up, down, strange, charm, top, bottom

<u>Hadrons</u>

- Baryons(1/2 integer spin) – protons, neutrons…
- Mesons(integer spin) – pions, lambda, …

Force Carriers

So what is it that allows Yoda to float a X-wing or the Emperor to shoot lighting?

A particle must somehow interact with the world around it otherwise we wouldn't be here having this talk!

All the particles mentioned so far interact with other particles by:

Exchanging even more particles!!!

Force Carriers

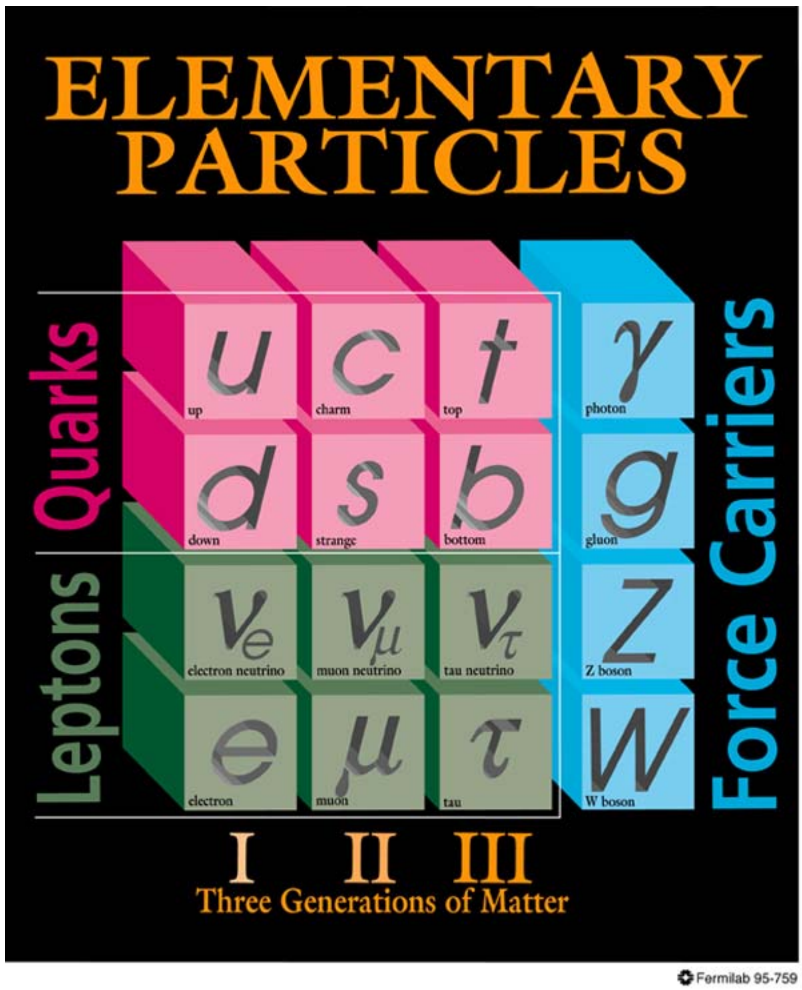
• Each force has its own force carrying particle(s), which *mediates* the interaction

- **Electromagnetism**
    - Photon
    - 2 charge values(+/-)
- **Weak Force**
    - Boson – W^+, Z^0, W^-
    - 3 charge values (+,-, 0)
- **Strong**
    - Gluon
    - 8 values of color charge
- **Gravity**
    - Graviton?

All of them also have the corresponding Antiparticles!!!

Force Carriers

And the starting line up is:



The heavier generations appear to be the same as the light generation, the only property that is different is mass!

The Forces: A Different Approach to the Standard Model

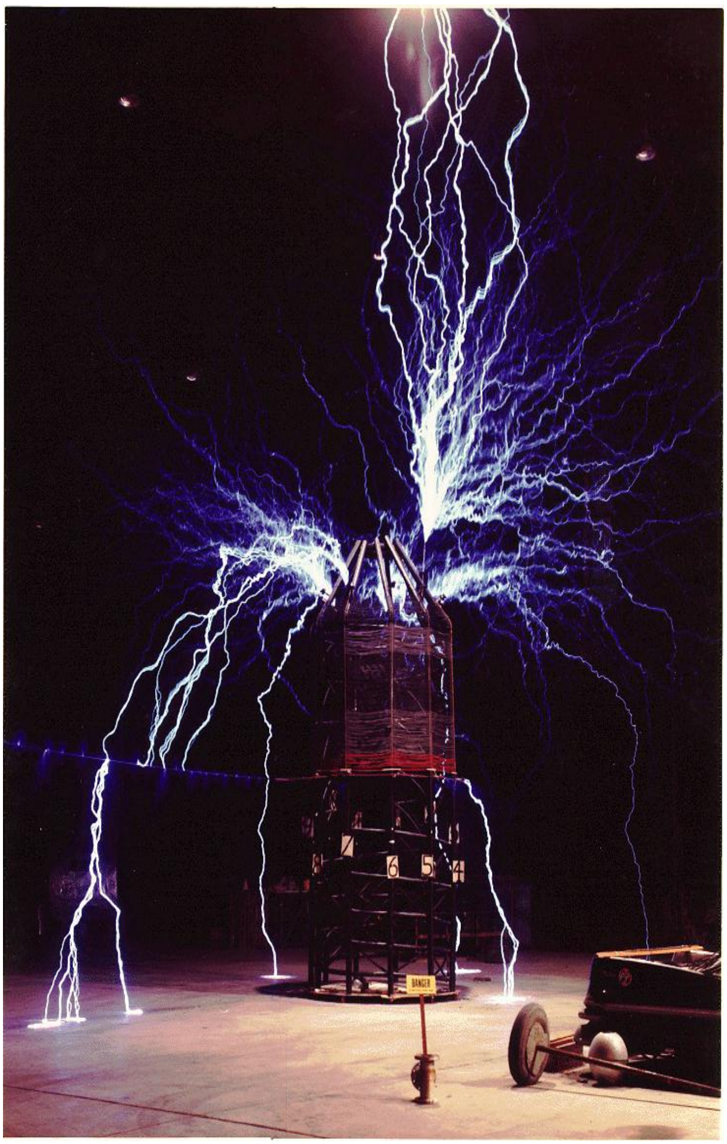
• The Standard Model is more than a collection of particles

• It is a description of how some of these particles interact in the world

• Think of it like a soccer game

The Forces: A Different Approach to Understanding the Standard Model

The Moves: Different forces and what they are.



Electromagnetism

• Probably the best understood force

• Macroscopic: infinite range, decreases over distance, infinite range = zero force

• Attractive or repulsive force between particles., caused by photons

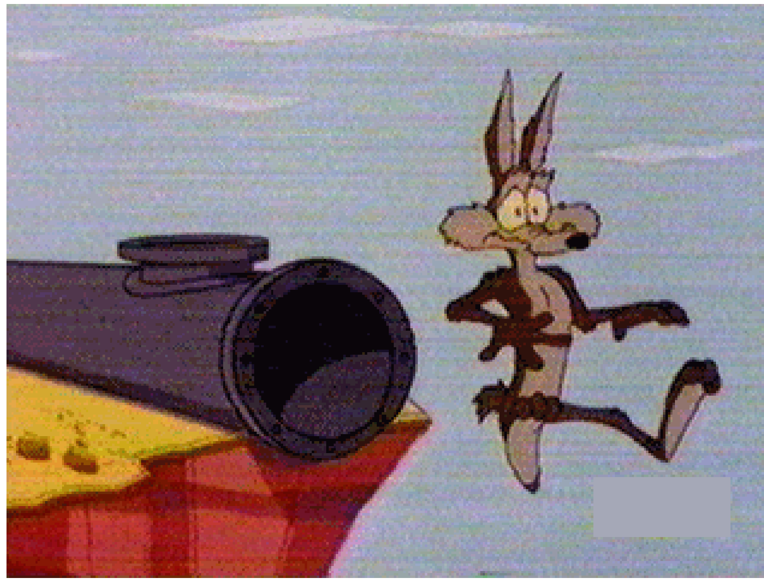
• Holds atoms together and keeps matter from collapsing under gravity

The Forces: A Different Approach to the Standard Model

Gravity

• Long range, Macroscopic, similar to electromagnetism

• Acts between particles with mass or energy



Got Gravity?

• Holds planets, stars, and galaxies together

The Forces: A Different Approach to the Standard Model

The Nuclear Forces

Weak Force

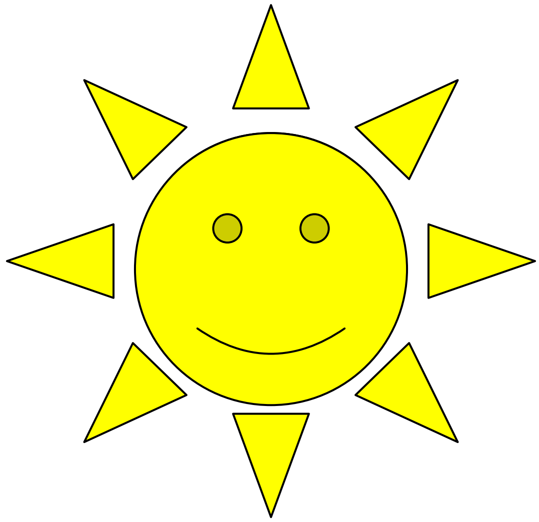
• Called Weak because the range over which it acts is very small, W, Z bosons are too massive to travel far

• Responsible for β decay of nuclei

• Causes heavier generations of matter to decay into, ups, electrons, and neutrinos

• Fusion in the sun requires the Weak force(inverse β decay

• Has been Unified with the Electromagnetic Force at high energy to form the Electroweak force



The Forces: A Different Approach to the Standard Model

The Nuclear Forces

Strong Force

• Strongest known force, but often is undetected

• Strength increases with distance, think rubber band

• Holds quarks, protons, neutrons, together

•Again, very short range, caused by exchange of gluons which bind Quarks together

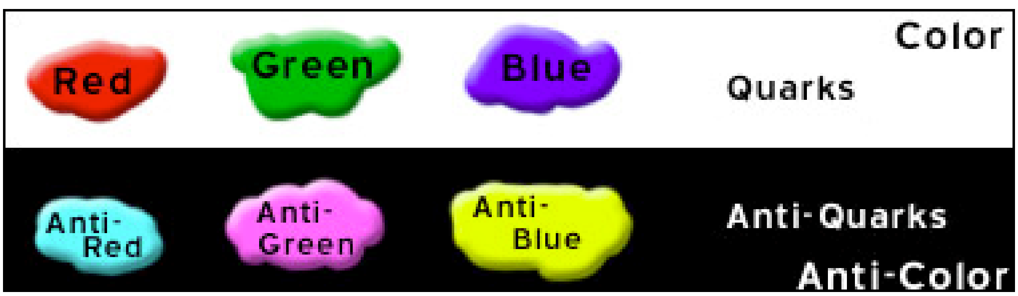
The Forces: A Different Approach to the Standard Model

A Word About COLOR

• Color is the "charge" type of quarks and gluons

• There are three "colors" of charge

• Red, Green, Yellow, with associated anti-color



• This works like light mixing, and you want to create white light

• This implies 2 or 3 quark combinations meaning baryons or mesons!

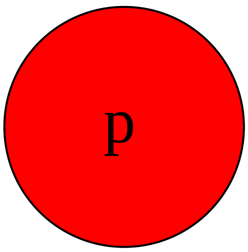
Building Matter

Now that we know the parts, we can look at how this creates the world around us!

Particle	Feels Force	Mediates Force	Electric Charge	Color Charge	Spin
Charged leptons (electron, muon, tau)	EM, Weak	-	-1	No	½
Neutrinos	Weak	-	0	No	½
Up, Charm, Top Quarks	EM, Weak, Strong	-	+2/3	Yes	½
Down, Strange, Bottom quarks	EM, Strong, Weak	-	-1/3	Yes	½
Photon	None	EM	0	No	1
Weak Bosons: $W^{\pm}$	EM, Weak	Weak	±1	No	1
Weak Boson: Z^0	Weak	Weak	0	No	1
Gluons	Strong	Strong	0	Yes	1

Building Matter

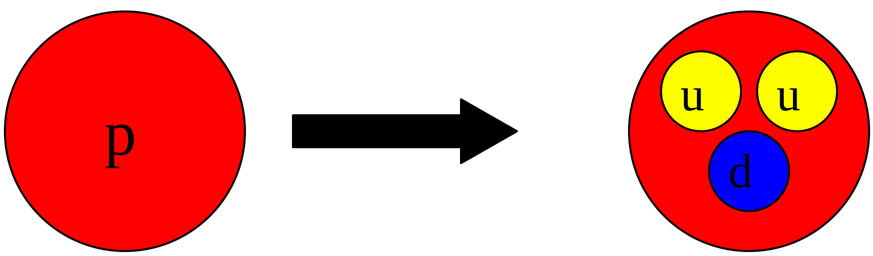
So now lets build a proton!



• Protons have a +1 charge

• They also have spin ½

• Use the simplest tools available, ups and downs!



Lets Check it!

- Charge: 2/3+2/3 –1/3 =1
- Spin: ½+ ½ - ½ = ½
- Similarly we create the neutron
    - u + d + d $\rightarrow$ spin =½ and charge = 0

Out of u and d quarks and electrons we create all matter!

Building Matter

A Reminder about Mass

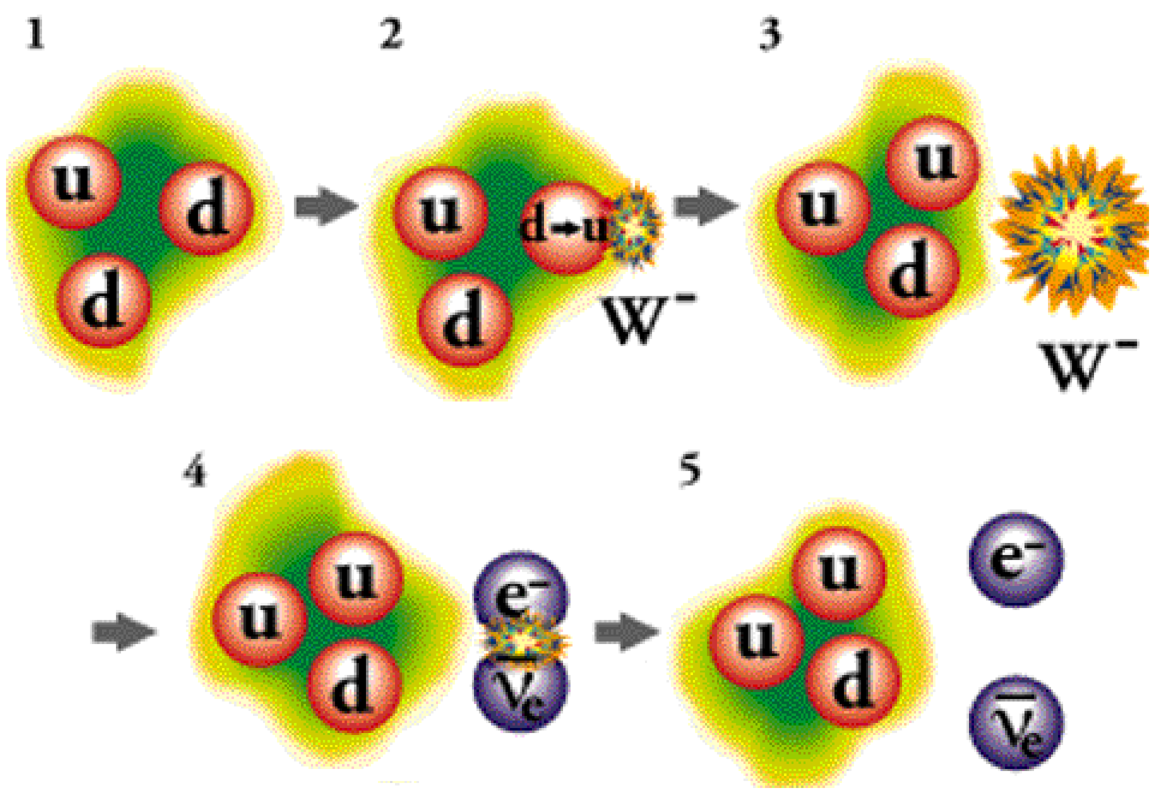
- u 5, d 10, s 200, c 1500, b 4500, t 175,000 MeV
- How does 5 MeV+5 Mev + 10 MeV = 1000MeV?
- Bosons! The Force carries for the strong force!

Building Matter

So why all this other stuff?

• At one point in time all the stuff we see was made up of the stuff we no longer see!

• Through the use of the Standard Model we can understand things better, for example beta decay:



Using the Standard Model

Playing the Game

Physics and the Standard model provide the rules by which to play the game:

- Conservation of energy/mass
- Conservation of momentum
- Conservation of charge

And a few new ones:

- Conservation of color
- Conservation of lepton number
- Conservation of spin
- Conservation of strangeness
- Neutrino type matches lepton type
- And others

There are also a few interesting moves concerning the Strong and Weak forces

Using the Standard Model

The Strong Force Revisited

We know that the strong force binds quarks together, but it also does something else.

• Sometimes these bonds can be rearranged, with quarks attaching to new partners

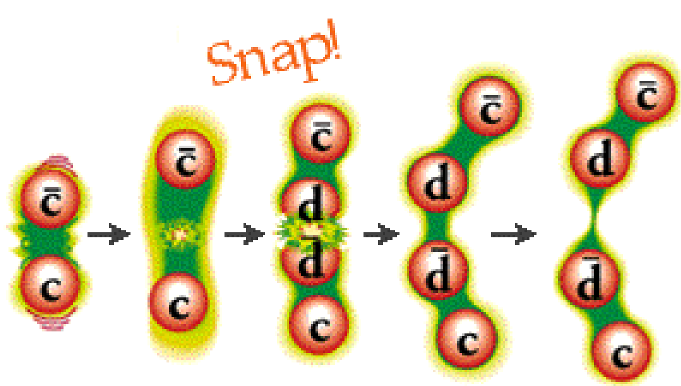
• For example:

$$\pi^- + p = n + \pi^0$$

$$\bar{u}d + udd = udd + \bar{u}u$$

• The strong force rearranged the existing quarks

• Also the strong force is so strong that:

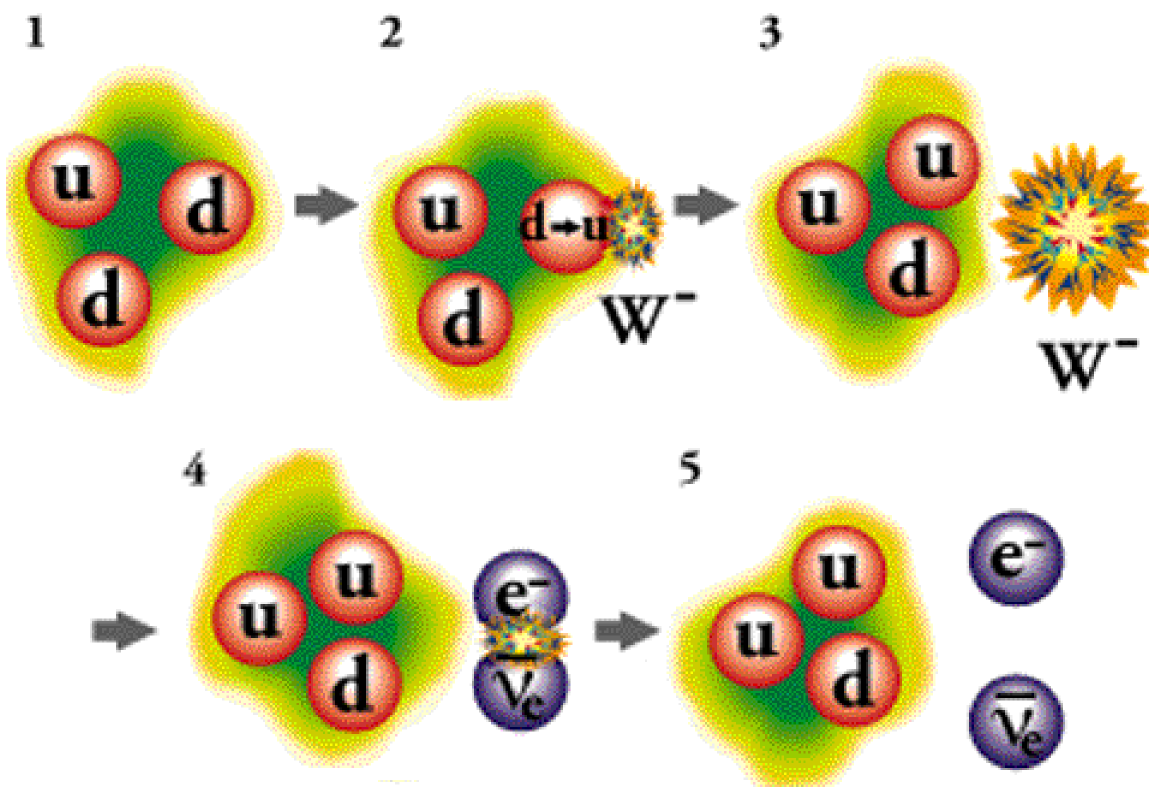


Using the Standard Model

The Weak Force Revisited

The Weak force is what allows one type of matter to change into another

• Recall the Beta Decay again:



• This also force allows quarks to change from one generation to another

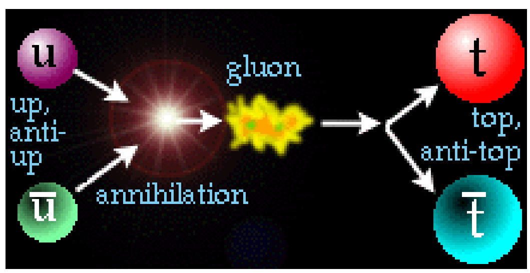
• The Weak force is how neutrinos interact

Using the Standard Model

Physicist use the rules of the standard model to study and predict things in the world.

• When physicists wanted to "see" the top quark they needed to create enough free energy to produce such a big object

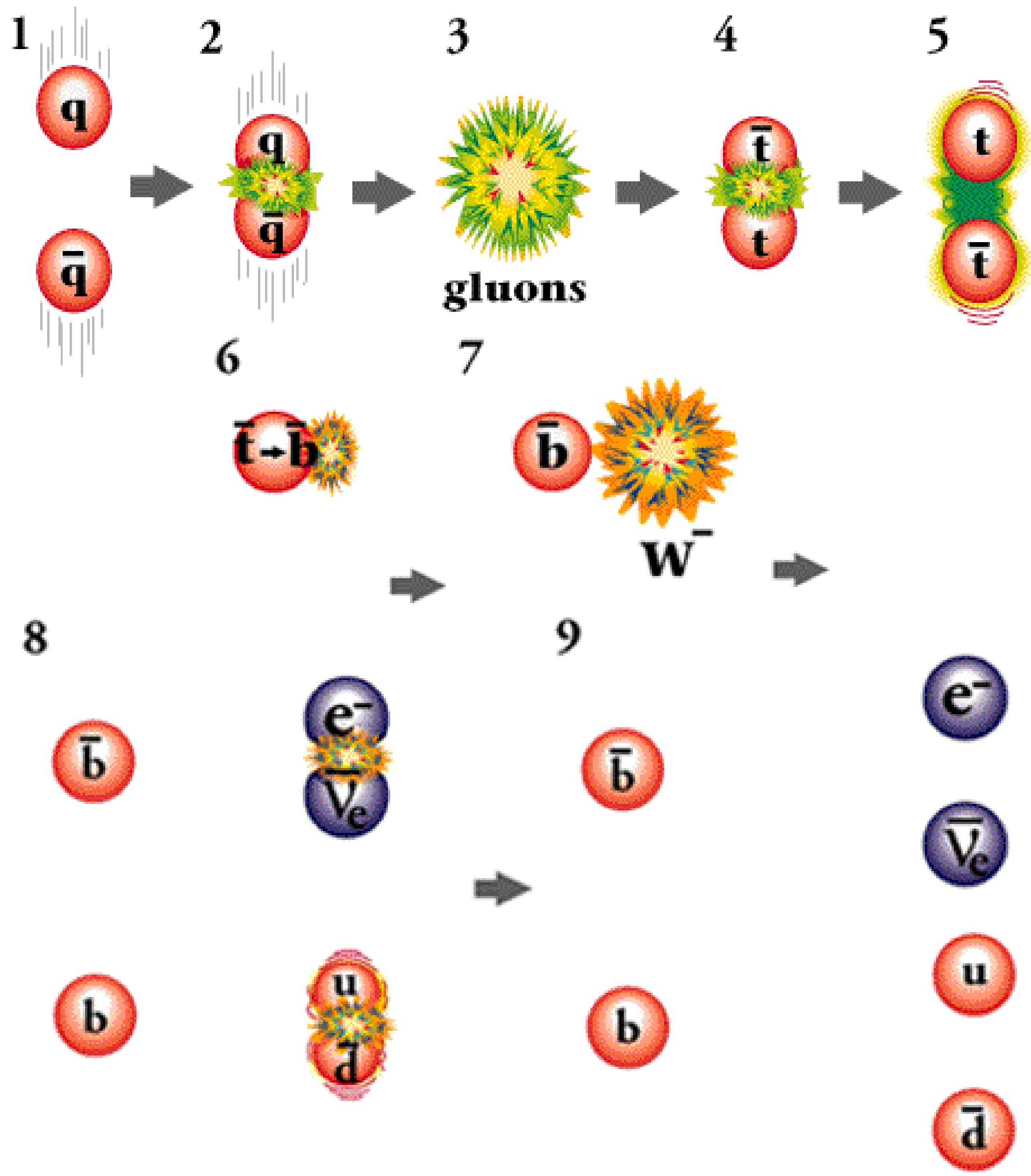
•By colliding protons and antiprotons we succeeded



• The problem is that the top doesn't stay around very long, so we look for a top signature, the sign that we know it was there

• We know what the signature is by the rules of the standard model!

Using the Standard Model



This whole process takes less than 10^{-20} seconds

Using the Standard Model

That was pretty messy to look at, which is why physicist use Feynman Diagrams

Simple:

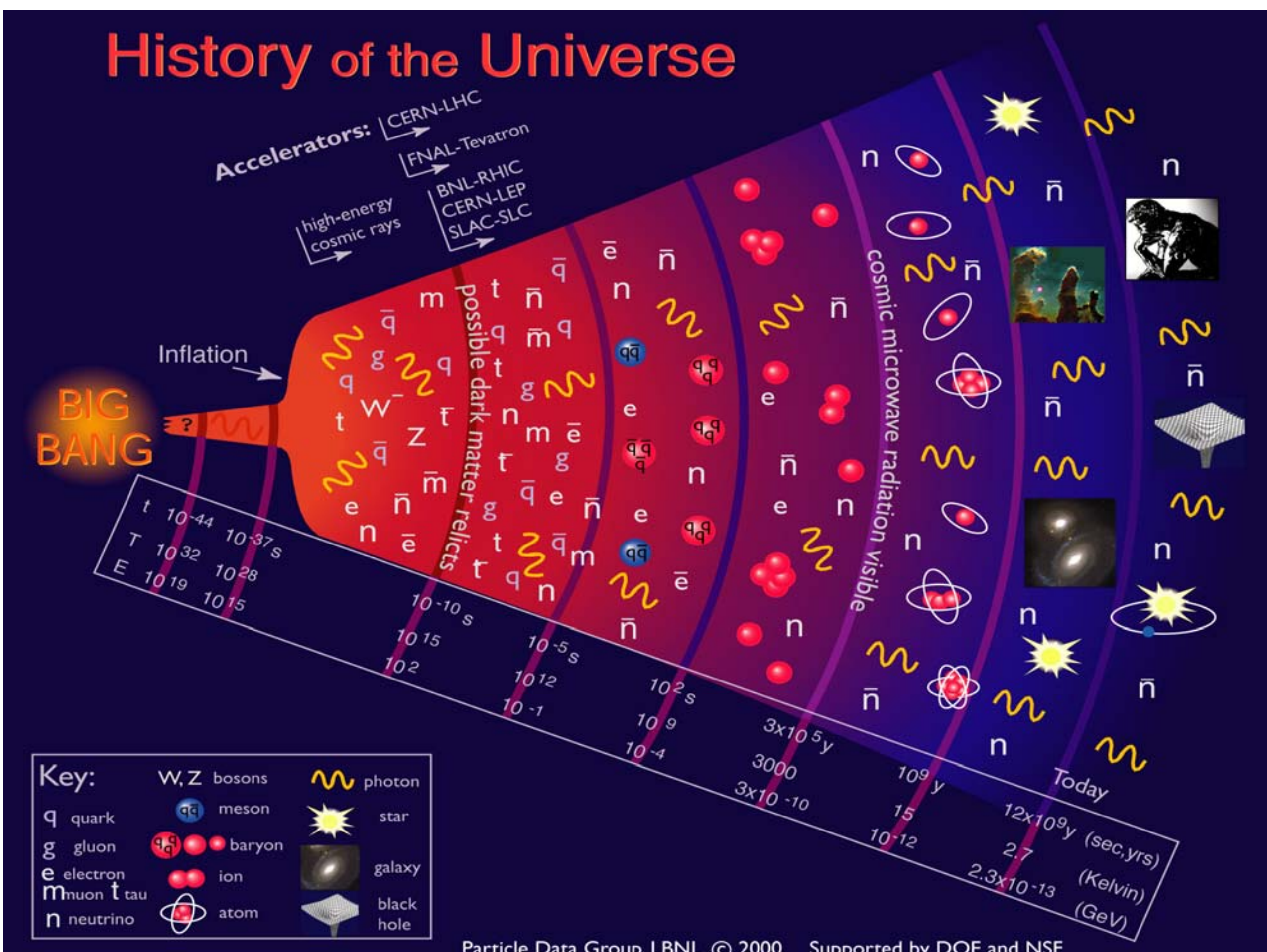
Complex:

Why?

• This is the basic concept of the Standard Model which provides a framework for how we think the universe is constructed

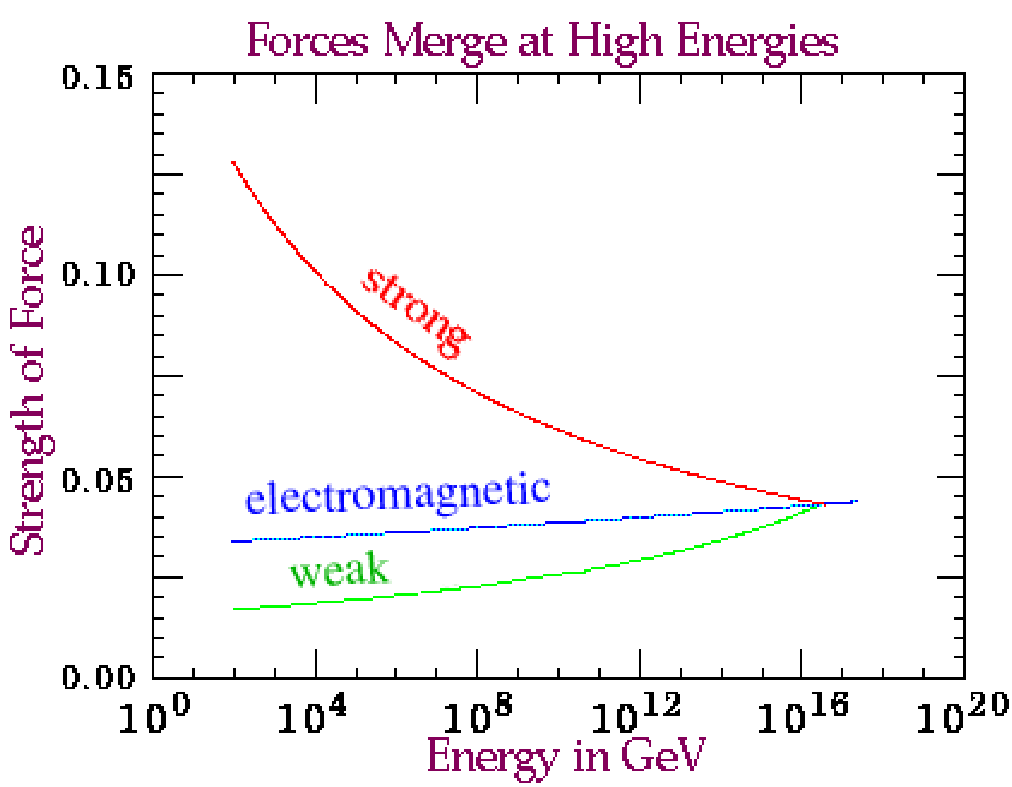
• It is a descriptive understanding, we are a long ways from why

• We are using it as a tool to try to reach the why of the universe



So What Else is Out There?

- New forces, particles, and rules
- Explanation for "Heavy Generations"
- Unification of the Strong and Electroweak force
- Higgs
- Supersymmetries
- Gravity
- New particles?



Where to go to Learn More

Books:

1. "A Tour of the Subatomic Zoo" – Cindy Schwarz
2. "The Particle Garden" – Gordon Kane
3. "The God Particle" –Leon Lederman

Websites:

1. www.particleadventure.org
2. www.fnal.gov
3. www.cern.ch

Finally, Ask your friendly neighborhood particle physicists!