The Four Fundamental Forces… and Beyond!

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- This could be a talk about anything
  - Army, Navy, Air, Coast Guard
  - Political, Economic, Social, Religious
  - …
- But we'll limit ourselves to physics and to "<u>the primary agents that cause motion or change</u>"*
- Describing these "primary agents" leads us into the microscopic world and …

extra dimensions!

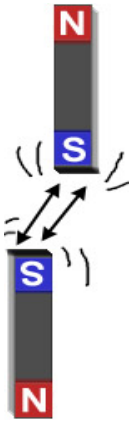
* Webster's has nearly 30 definitions of force!

The Familiar Forces

Gravity
Frictional (Static & Kinetic)
Centrifugal/Centripetal
Tension
Normal Forces

Newton's Laws
1687
Force =
Mass * Acc.

Electrical
Magnetic



James Clerk Maxwell
1865
Maxwell's Equations

Unification

- There's a natural tendency toward unification of forces
- For instance electrical and magnetic phenomena where unified by Maxwell's equations into electromagnetism.

- In essence all electrical and magnetic phenomena can be described by the motion of charged particles.

And a drive towards simplicity

- All of the "familiar forces" are due to just gravity & electromagnetism.
- Consider friction: this is just the residual force left over from the charged atoms on the two surfaces interacting electromagnetically! The same can be said for the normal and tension forces.
- As for centripetal forces, these can be due to gravity, if you're a satellite, or the normal force (electromagnetism), if your in a car and restrained by your seat belt!

The Situation ~1900

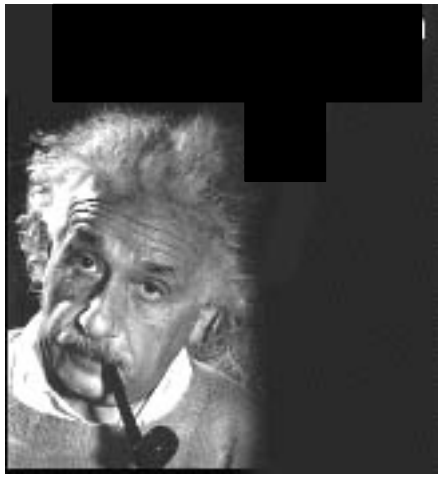
- So at the turn of the last century most phenomena could be explained by
  - gravity
  - electromagnetism.

- But some annoying things started cropping up because of improved instrumentation:
  - X rays (Roentgen 1895)
  - Radioactivity (Becquerel 1896)
  - The electron (Thomson 1897)
  - The nucleus (1911 Rutherford)

The Quanta

All these discoveries led to the description of matter and radiation as particles or small quanta

- The quantum idea (Planck 1900)
- Light as quanta (Einstein 1905)
- The nucleus (Rutherford 1911)
- The atom (Bohr 1913)

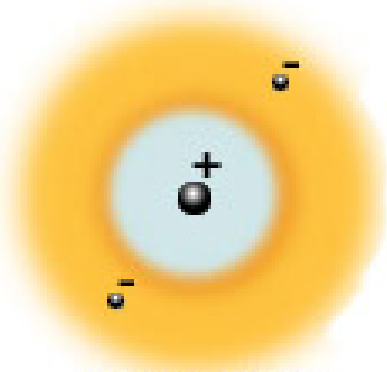


The Atom*

- Let's consider the atom: In 1900 it was thought to be a solid sphere
- After the quantum revolution it was understood to be composed of a nucleus and electrons.
- The electron has negative charge and the nucleus positive charge. The entire thing is held together by electromagnetism

*By the way atom is a misnomer since it's Greek "ατομον" for "that which cannot be divided"!

1900



Present Day

(I am the Very Model of a Modern Major Atom)

Light as a Manifestation of a Fundamental Force

- By emitting or absorbing a photon, the electron can change its average position or energy in an atom.
- In every day life, the illumination from your light bulb is just a very great number of photons emitted from the excited filament atoms.
- This is a classic electromagnetic interaction and our first manifestation of a fundamental force!

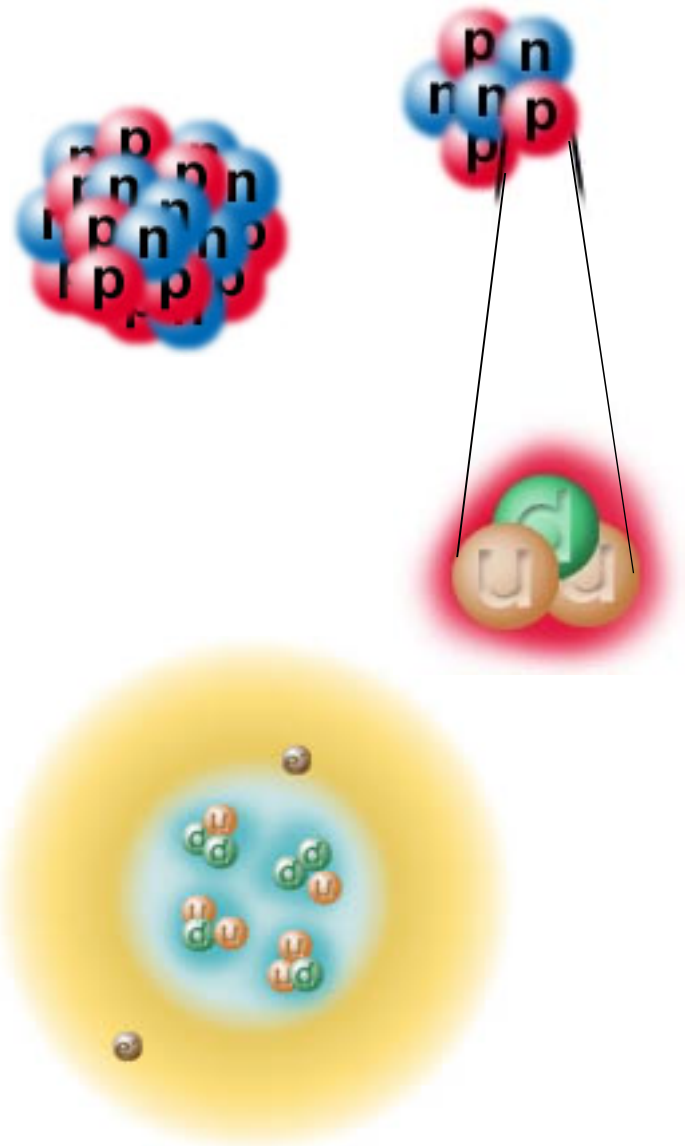
A Characteristic of Fundamental Forces

- As the light bulb hinted, charged objects interact by exchanging photons.
- In the atom the electron and nucleus are held together by exchanging photons.
- In fact all fundamental forces involve the exchange of a fundamental particle.

… to go any further in our discussion we need to enumerate the fundamental particles

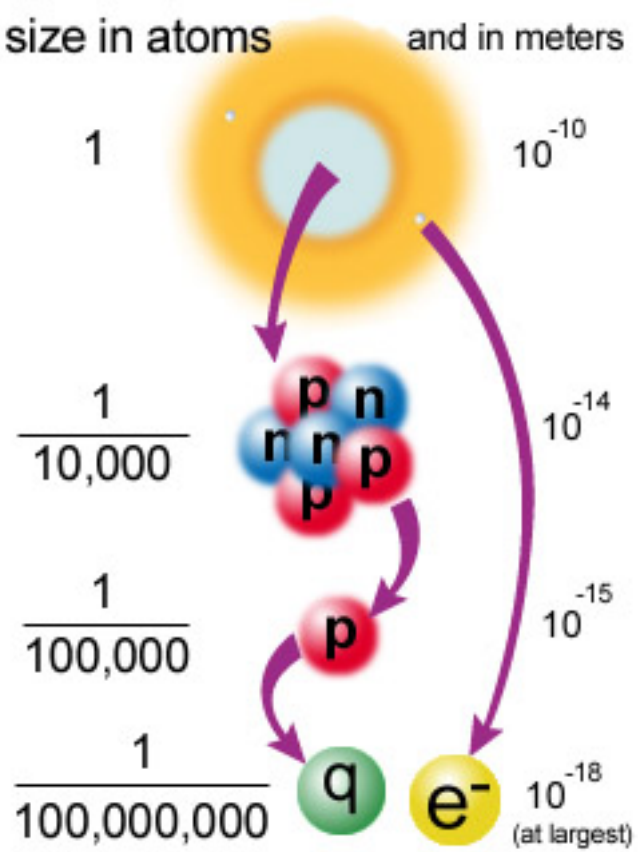
The Nucleus and the Atom

- Nowadays we know the nucleus to be made of protons and neutrons
- And the protons and neutrons of quarks!
- So that a complete picture of the atom would include quarks and electrons.



Scale

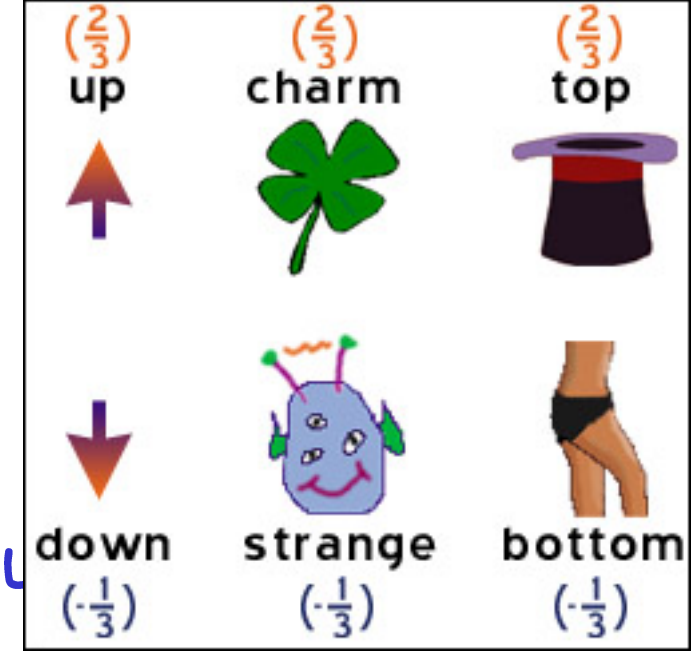
- Let's just take a small detour to consider the scale of the atom
- In fact the tiny electrons and quarks have no observed structure and are for all intents and purposes fundamental.



The Standard Model

- The crowning achievement of particle physics is a model that describes all particles and particle interactions. The model includes:
  - 6 quarks (those little fellows in the nucleus) and their antiparticles.
  - 6 leptons (of which the electron is an example) and their antiparticles
  - 4 force carrier particles (of which the photon is an example)
- **All known matter is composed of composites of quarks and leptons which interact by exchanging force carriers.**

The Quarks*



- There are three pairs
- The up and down are constituents of and most matter.

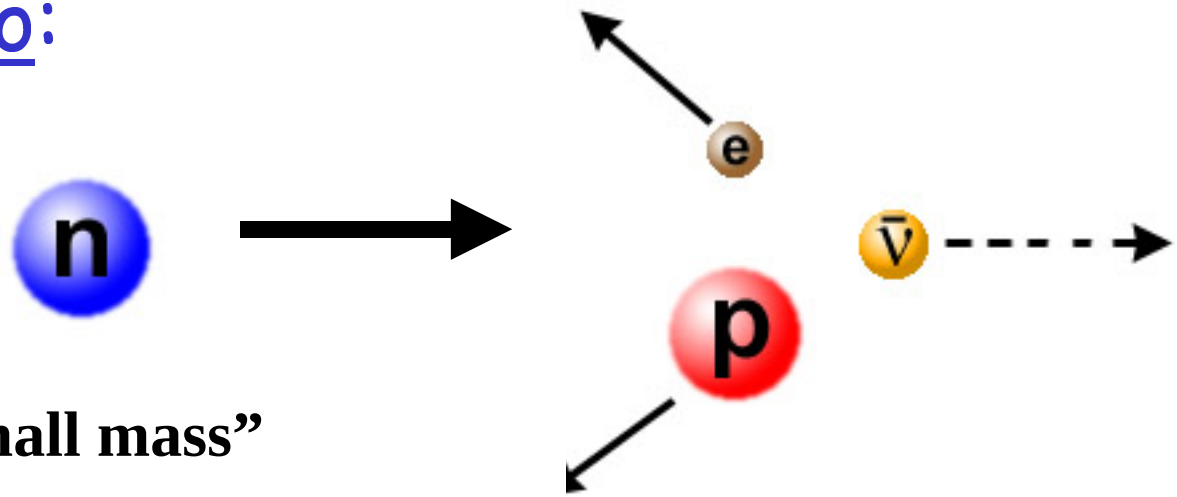
neutrons = u

- The other particles are produced in energetic subatomic collisions from cosmic rays or in accelerators like Fermilab (where they are also studied.)

***The name comes from James's Joyce's *Finnegan's Wake*, "Three quarks for Muster Mark!"**

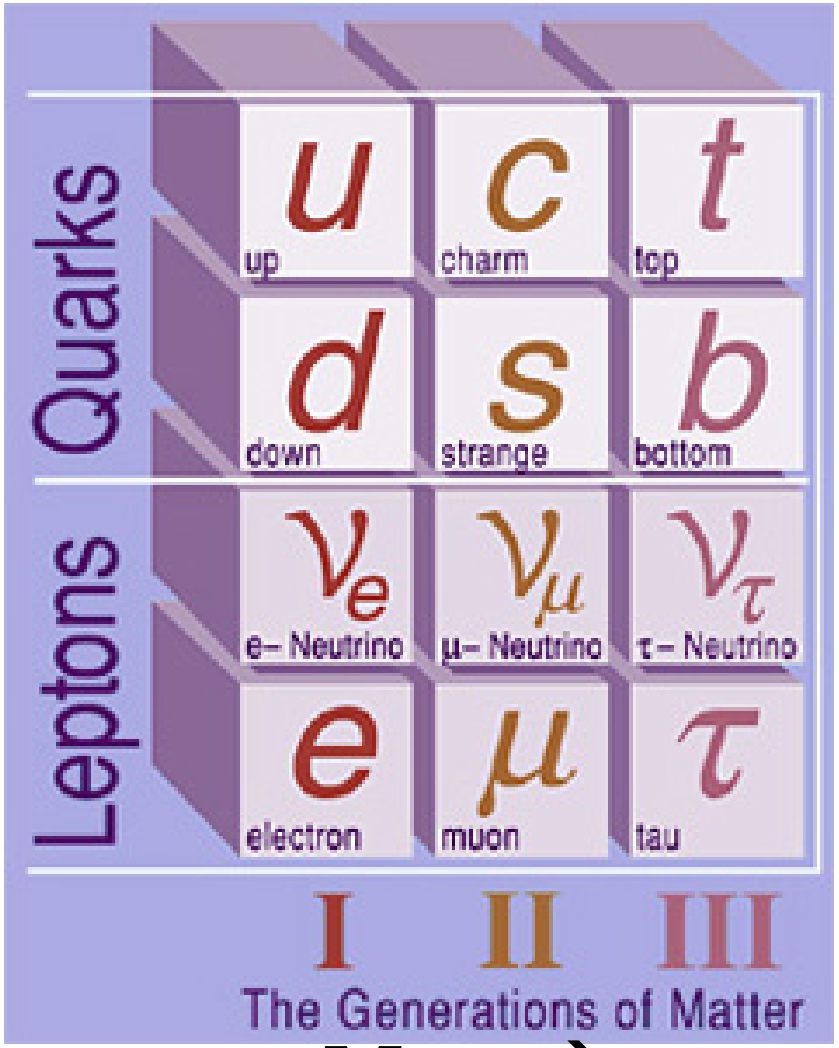
Leptons*

- Leptons are generally lighter particles and are most readily observed in radioactive decays.
- The best example is neutron decay into a proton, an electron, and a neutrino:



*Greek for "small mass"

Periodic Table of Fundamental Particles



Mass →

+2/3

−1/3

0

−1

Add Antiparticles

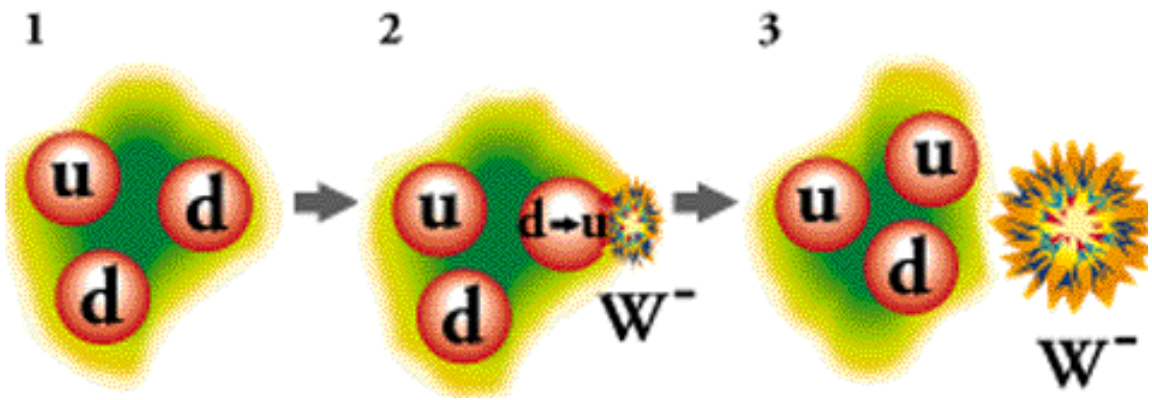
Families reflect increasing mass and a theoretical organization

u, d, e are "normal matter".

Because of the charge quarks, electrons, muons, and tau's participate in EM

The Weak Force

- Radioactivity, in particular the neutron decay we discussed earlier, is actually a manifestation of the weak force
- At the quark level, a down quark in the neutron decays into an up quark, by emitting a W boson.

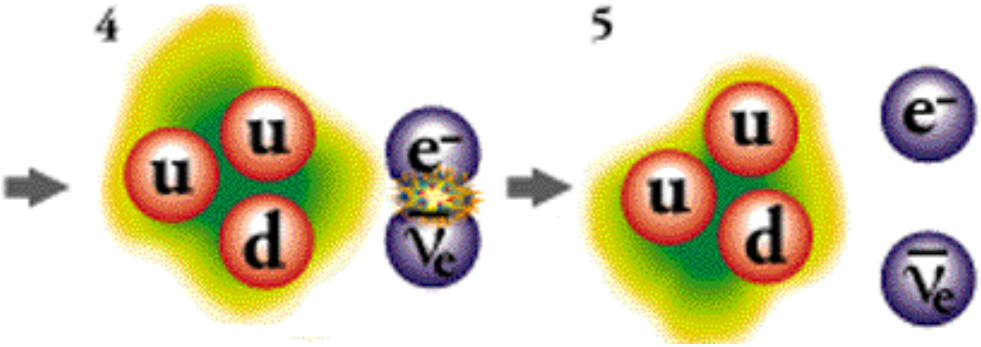


- The heavy W boson is the carrier of the weak force.

The Weak Force (continued)

- Since the W is very heavy (80 times the proton itself), it takes a long time for quantum fluctuations to gather the where-with-all to support the decay. Thus a "weak" decay.

- Finally the W itself decays into leptons



The Weak Force (continued)

- The decay $n \rightarrow p e^- \bar{\nu}_e$ is a manifestation of the weak force
- The weak force involves interactions between the quarks and leptons
- In this case through the exchange of the carrier W.
- <u>There are three weak carriers W^+, W^-, and Z^0</u> Discovered 1983.

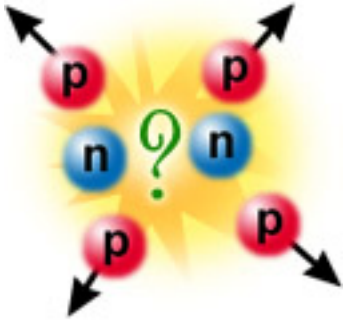
A Brief, First, Consolidation

- We've enumerated two fundamental forces.
- Electromagnetism which occurs between charged particles and is carried by the photon, γ.

- Weak force which occurs between quarks and leptons and is mediated by the intermediate vector bosons, W^+,W^-, and Z^0.

The Problem of the Nucleus

- Why doesn't the nucleus - full of positive protons that repel one another and neutral neutrons - blow itself apart?



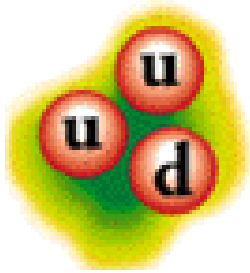
- Gravity doesn't work since it's much too weak compared to electromagnetism.
- There must be yet another force around!

The Color Charge

- Well it turns out quarks have another quantum number or charge called "color charge".
- The force between these color charges is extremely strong.
- Two quarks interact by exchanging the strong carrier dubbed the "gluon"
- Gluons themselves have r charges

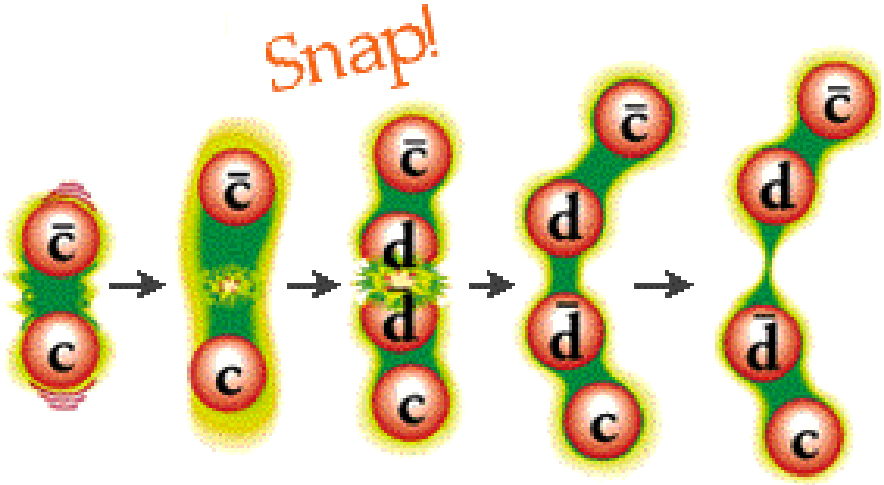
The Color Charge (continued)

- There are three color charges named: "red", "green" and "blue".
- These names are mathematical identifiers and have nothing to do with visible colors.
- Quarks are bound in a particle, like the proton, by madly exchanging gluons and forming a binding color field:



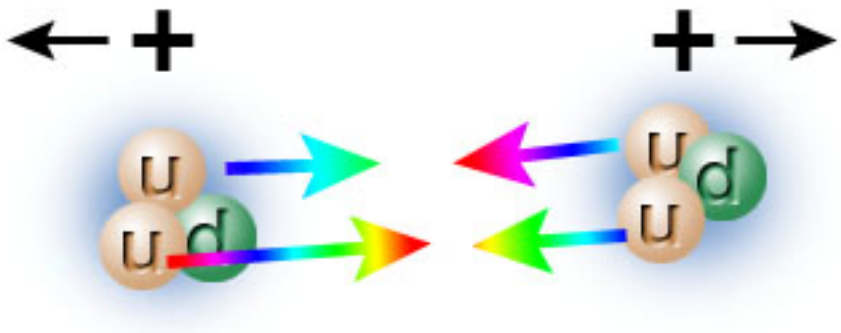
The Color Charge (continued)

- Free quarks cannot be observed because of this strong field
- If two quarks a pulled away from one another the field breaks into a new pair of quarks:



The Color Charge (continued)

- Now back to the nucleus!
- The residual strong field between the protons and neutrons overwhelms the repulsive electromagnetic force and holds the whole thing together



A Second Consolidation

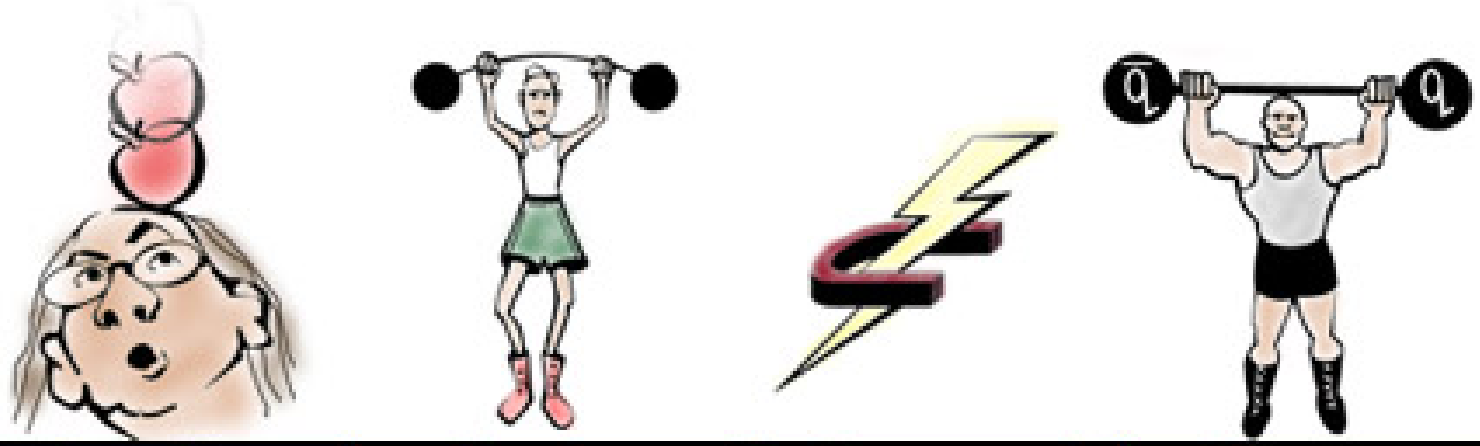
- The weak force occurs between quarks and leptons and is mediated by the massive intermediate vector bosons W^+,W^-, and Z^0

- The electromagnetic force occurs between electrically charged particle and is mediated by the massless photon.

- The strong force occurs between color charged particles and is mediated by the massless gluon.

Gravity

- Although a deep understanding of gravity has been around the longest it is not understood at the carrier level.
- The graviton has not been discovered.
- Still since this is a very weak force the Standard Model works very well in the absence of a full description



	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

10^{-37} weaker than EM

Explained by complete theory

We could stop here but…..

A Few of the Unsolved Questions

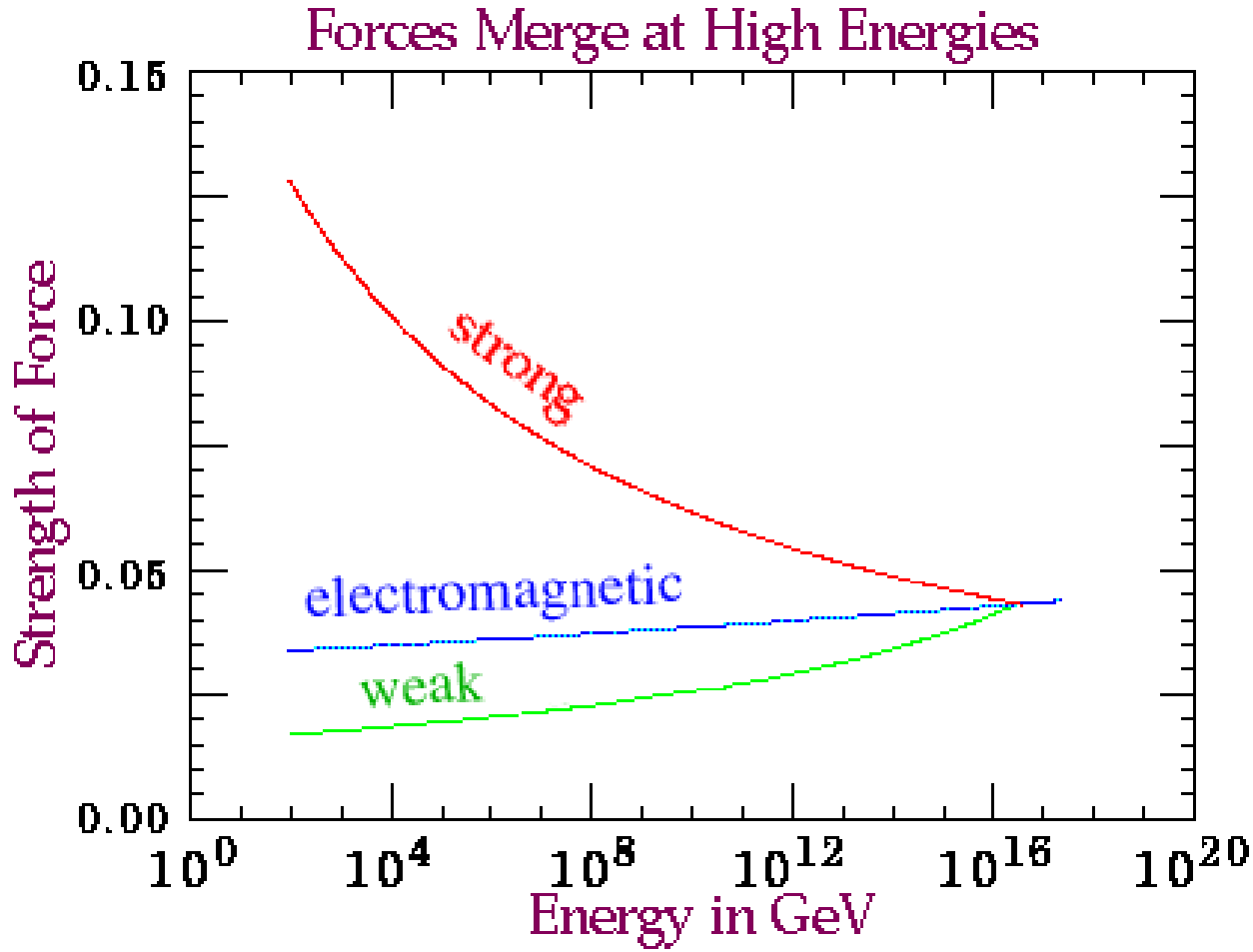
- Can the forces be fully unified?
- How do particles get mass?
- How does gravity fit into all of this?

The Electroweak Unification

- Remember that quarks and leptons interact through the weak force?
- Note the quarks, leptons, and bosons all carry charge so they can also interact electromagnetically. This is a big clue!
- It turns formally (or mathematically) that electromagnetism and the weak force are manifestations of the same underlying force: the el veak force.

Grand Unified Theories(GUTs)

At very high energies all interactions merge to a single strength.



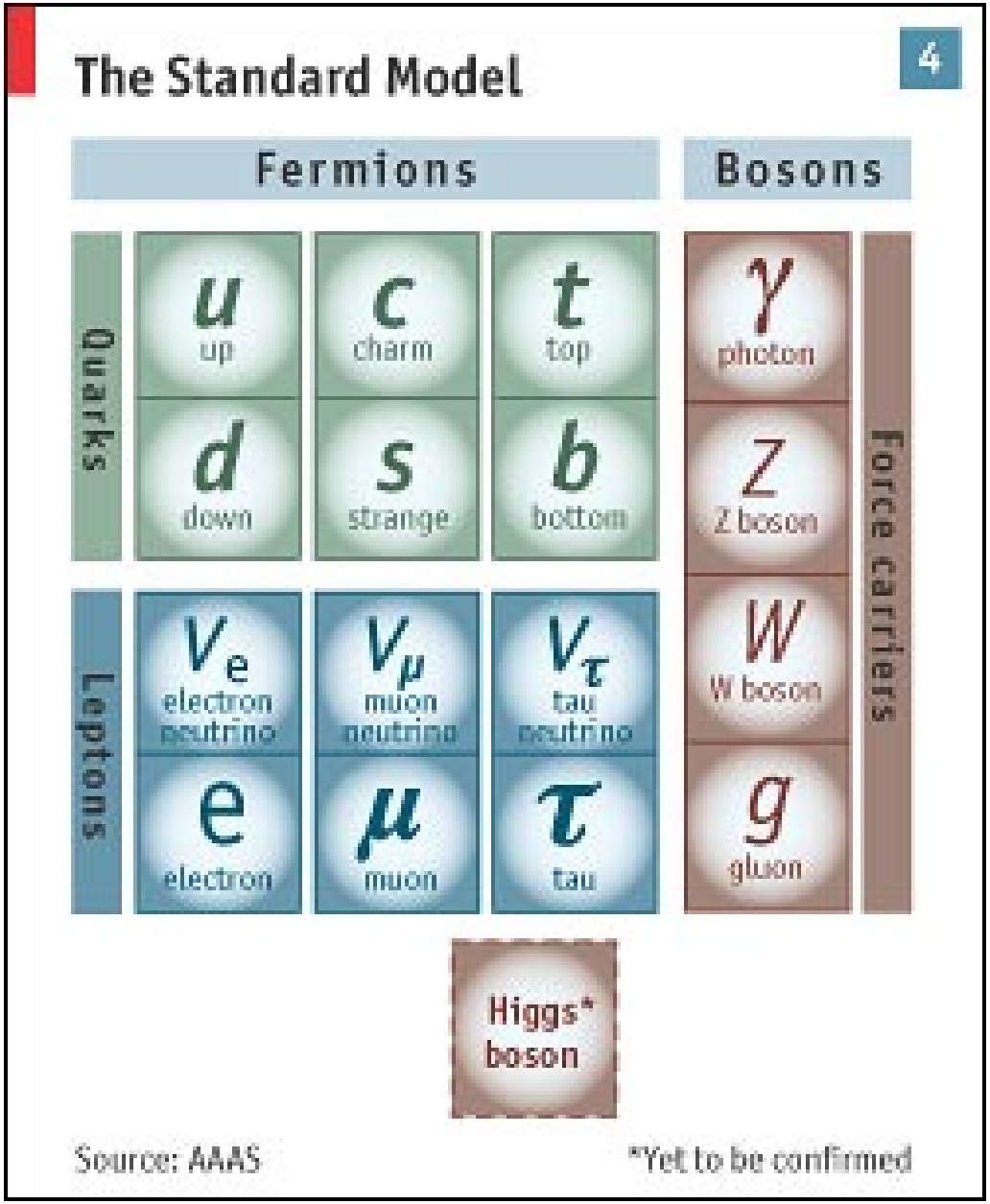
The Higgs Particle

- The electroweak unification postulates the existence of the Higgs Particle, H.
- This particle or field interacts with all other particles to impart mass.
- The experimental program at Fermilab in Illinois and the Large Hadron Collider in Europe are dedicated to the search for this particle.
- It's discovery would be an achievement of the highest order – reaching an understanding of the origins of mass!

An Accelerator

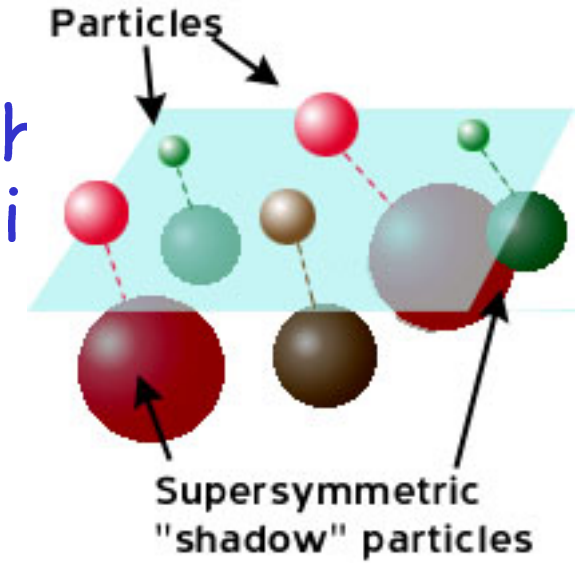
A Detector

International
50-100 institutions
500-1000 physicists
10 year lifecycles
$100M
Barn-sized


The Standard Model
4
Fermions
Bosons
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
e
electron
μ
muon
τ
tau
Force carriers
γ
photon
Z
Z boson
W
W boson
g
gluon
Higgs* boson
Source: AAAS
*Yet to be confirmed

Beyond the Standard Model

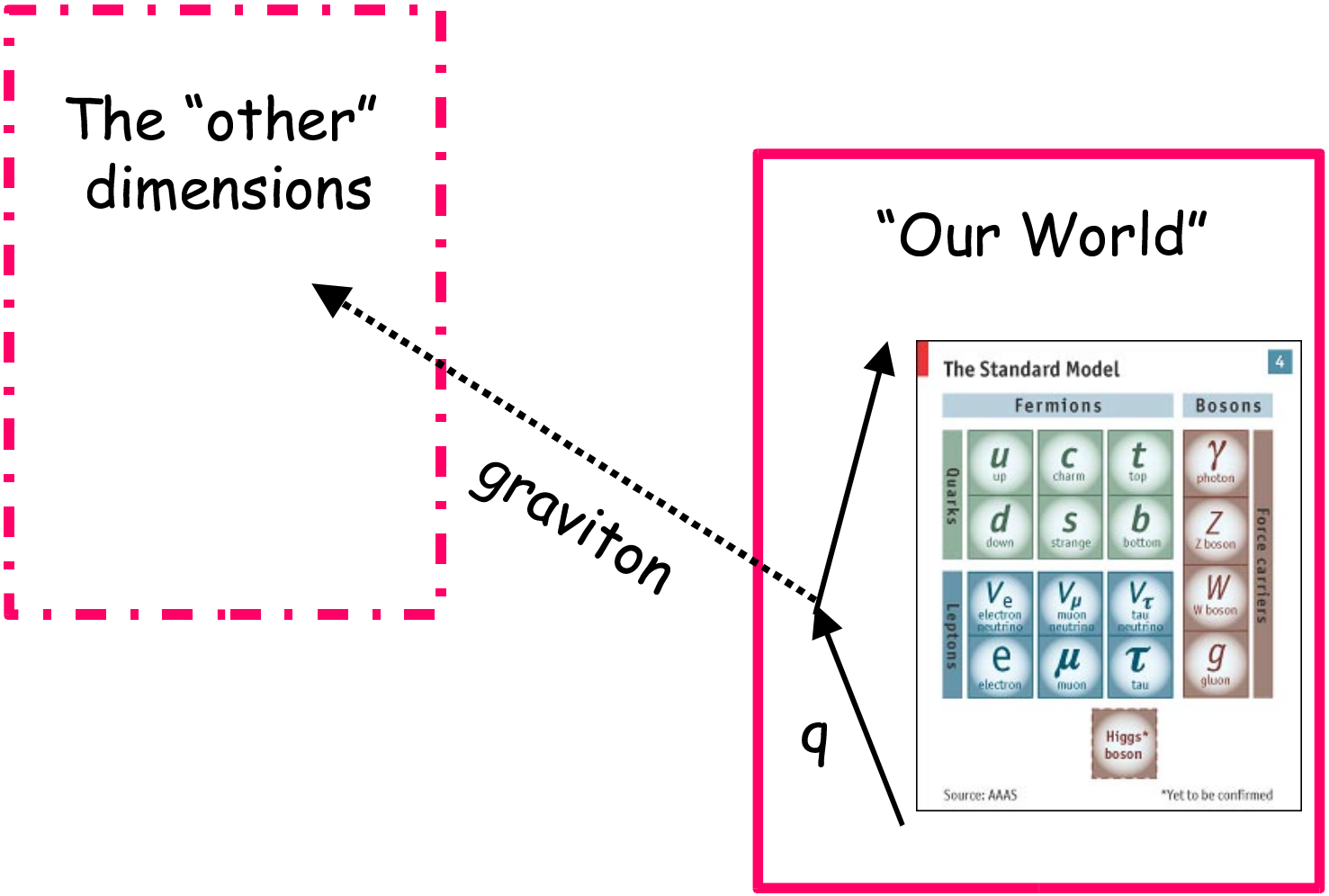
- The desire to explain gravity and unify it with the other forces has led to the ideas of Supersymmetry (SUSY) and Extra Dimensions (to name just two!)
- In SUSY every particle and force carrier has a massive partner. Squarks, slectrons…
- Since they are massive they've not been produced in current machines. The discovery requires more energetic
  – something which th
  enthusiastically pursui



Extra Dimensions

- Amazingly enough an 11 dimensional world (time, 3-D, 7 very small less than 1mm in size) can accommodate a fully unified theory!
- Only gravity can communicate to the other dimensions and so it's "strength" is diluted in ours. That is, the graviton can spread it's influence among all 10 spatial dimensions.
- Experiments are underway searching for signals of these dimensions.

Think of our world and the other dimensions as just 2-d planes…



In Conclusion

The four fundamental forces: gravity, weak, electromagnetism, and strong

- All but gravity explained by the Standard Model of particle physics
- Theory and experiment give tantalizing hints of full unification!