The Standard Model of Particle Physics

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Let’s look at what it is…

- Description of fundamental particles – **quarks** and **leptons**
- Three out of Four (Forces) ain’t half bad
  - Electromagnetic
  - Strong
  - Weak
  - **Electroweak force**
  - EM and Weak force are two sides of a coin
- **Rule Book** – Conservation of Energy, Charge, momentum
A quick look

ELECTROMAGNETIC PARTICLES

Quarks

Leptons

Force Carriers

Building Blocks of Reality

Three Generations of Matter

Fermilab 95-759
Our Toolbox

- **Particles** interact by exchanging other particles
- **Quantization** – same thing
- **Spin**
  - Bosons – Stack em up
  - Fermions – Can’t be in same place at the same time (Pauli Principle)
- **Antimatter**
  - Everyone needs a brother
Quarks

✓ Affected by
  ► strong force
  ► weak force
  ► electromagnetism
  ► gravity

✓ Fractional charge
✓ Spin 1/2
✓ Three generations differing only by mass
✓ Up and Down quarks make up protons & neutrons!
Leptons

- Affected by weak force, electromagnetism, gravity
- Charged Leptons – 3 copies: electron, muon, tau
- Neutrinos – 3 copies: no charge, tiny mass, Oscillate
- Have spin 1/2
- Electron is component of ATOMS!
The Four (or Three) Fundamental Forces

Gravity

Strong Force

Electromagnetism

Weak Force
Electromagnetism

- Mediated by photon (light) exchange
- Infinite Range: acts on cosmic and atomic scales, responsible for chemistry
- Acts upon objects with electric charge
Weak Force

- Responsible for decays of massive particles into lighter ones
- Cause of $\beta$ – decay and fusion in Sun
- Short range force mediated by MASSIVE $W^+$, $W^-$, and $Z^0$ particles
Massive W and Z particles – just how massive?

- More **MASSIVE** than anything we’ve ever found except Top quark

- **Q:** So how can a particle decay by something more **massive** than itself?

- **A:** Nature Cheats: Heisenberg’s Uncertainty principle
  \[ \Delta p \Delta x \geq \frac{\hbar}{2} \text{ or } \Delta E \Delta t \geq \frac{\hbar}{2} \]
Strong Force

- Strongest force, quarks/gluons are only particles that it affects
- Force mediated by gluons
- Quarks/gluons have color charge, analogous to electric charge with a few differences

So how does color work?
Not So Short Story
Quarks have **Color**

- Three types of **color charge**, Red, Green, Blue and associated **anti-color charge**

- And....

- Eight different **color/anti-color combinations** that **gluons** can make
Quarks Unite!

- Quarks exchange massive amounts of gluons creating a color field.
- Each gluon exchange and absorption changes the color of a quark.
- So how does this hold quarks together?

Important! Gluons are self-interacting. So what?! Well... this leads to.....
More Energy in pulling quarks apart = stronger force holding em’ together

Proton
Confinement

Energy used to pull two quarks apart literally pulls particles into existence
Assembling the Atom

- Residual forces felt between protons/neutrons from gluon field. It's this that binds nucleus together.
- Electrons orbit nucleus.

And... Atoms!!
End of
Not So
Short Story
Three types of color charge, Red, Green, Blue and associated anticolor

And....

Eight different color, anticolor combinations that gluons can make
Color has to be “neutral” for quarks to combine

- A color and anticolor cancel each other out (“neutral”)
- Red, Green, and Blue make “neutral” or “white”

So, the following can form

**mesons**: quark-antiquark pair (e.g. pions)

**baryons**:
- Three quarks, different colors (e.g. protons, neutrons)
- Three antiquarks, different anticolors (e.g. anti-protons, antineutrons)
As two quarks are separated, energy used creates a lot of **gluon-gluon** activity.

Increasing **gluon-gluon** activity causes more force between particles.

Why the **Strong force** increases with distance.

**Confinement**
Assembling the Atom

Residual forces are felt between nucleons from the gluon field. It is this that binds the nucleus together.

Electrons orbit the nucleus.

And... Atoms!!
Electroweak force

- **Weak** and **electromagnetic** forces unified into **electroweak** force
- Theory predicted the $W^+$, $W^-$, and $Z^0$ bosons, relates them to **photon**
- Requires another particle called **Higgs boson** which gives particles **mass**
Pop Quiz

Particles interact by:
Pop Quiz

- Particles interact by:
  - Exchanging other particles/force carriers
Pop Quiz

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- Things with electric charge interact by:
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- For $\beta$ – decay, the particle that is exchanged is:
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- Particles interact by:
  - Exchanging other particles/force carriers

- Things with electric charge interact by:
  - Photon/light

- Things with color interact by:
  - Gluons

- For $\beta$ – decay, the particle that is exchanged is:
  - $W^+$ or $W^-$
Protons and Neutrons are made up of:
Pop Quiz – part II

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Quarks (up and down quarks)
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  - Neutrons and protons, quarks, nucleus
- Weak force is responsible for:
  - $\beta$ – decay, fusion in sun, decay of massive particles
Unsolved Mysteries

- Gravity
- Why three generations
- Can’t predict a particle’s mass, oops, Higgs?
- Matter/Anti-Matter asymmetry
- Dark Matter

Kinks in the Standard Model
The Horizon

- Supersymmetry
- String Theory
- Extra Dimensions
- Dark Matter
- Dark Energy
- Grand Unified Theories
...and a look at what it is not

- A complete theory
- Description of gravity
- Explanation of heavy generations of leptons and quarks
- Unification of strong and electroweak forces
- Definitive explanation on the origins of mass
But what does all this mean?

- What are quarks and leptons?
- What are the force carriers?
- What do they do?
- And how do we get from weird sounding particles to the world around us?
- How did anyone come up with all this?!

We’ll need some tools and then we can dive in
Spin

- Analogous to spinning top, but nothing is really “spinning”
- Intrinsic Property of all Fundamental particles
- All have magnetic moments which is what helped lead to the idea of spin
- Can be integer (boson) or odd half-integer (fermion)
- In the case of fermions, spin can be up (↑) or down (↓)
- Conserved quantity
Antimatter

- Every particle has an antiparticle
- All properties the same except spin, charge, and color opposite
- Particle and its antiparticle annihilate upon contact into pure energy
- Problem of why more matter than anti-matter in the universe
Bosons and Fermions

Boson = particle of integer spin
- E.g., 0,1,2,…
- Examples: Photon, W, Z, gluon, He-4 nuclei, Oxygen 16
- Multiple particles can be in the same state

Fermion = odd half-integer spin
- E.g., -1/2, 1/2, 3/2,….
- Examples: Electron (all leptons for that matter), quarks, He-3
- Pauli Exclusion principle – one particle per quantum configuration
The Wild World of Conservation Laws

- **Symmetries** exist in the equations of the Standard Model – theorem: for each symmetry a conservation law

A few most of us are familiar with

- Mass-energy, momentum

And some a little less familiar

- Charge, Color, Spin, Angular Momentum, baryon #, lepton #

These limit what is possible....
Feynman Diagrams

The Basics

Embodies Quantum Theory in Simple Diagrams

- Arrow of time → either points up or to the right (conventions)
- Arrow in direction of...
  - time = particle
  - opposite = antiparticle
- Events can be rotated in any direction to represent different processes
Arrangements limited by conservation laws….
i.e. cannot replace the photon with an electron

Electrons in this case represent real particles
Photon in this case is a virtual particle
Gravity

- Attractive force between any object with mass or energy
- Outside of the Standard Model, described by General Relativity
- Infinite Range, weakest of the forces, dominates astronomical scales
- Graviton predicted as force carrier
Differences between Weak & EM force

• Range of EM = $\infty$
  Range of Weak = atomic scale

• Photon is massless
  Ws, Z are MASSIVE

• EM conserves parity
  Weak violates parity

• EM is…uhh, a strong force
  Weak force is, err, well, weak
Mathematics

- The EM force is proportional to ‘e’, the electric charge

- The Weak force is proportional to ‘g’, which behaves the same way in equations as ‘e’

- Both forces can be described by the same equations (Called Lagrangian)

And....
Not so Different

- $W^+, W^-, Z^0$ and photon are very similar except for huge mass difference
- $W^+, W^-, Z^0$ predicted by this theory and found (and the Z with no experimental backing!)
- Ws, Z, and photon interact very similarly at higher energies and short distances
Why do EM & the Weak Force look so different?

- Electroweak symmetry breaking...
- This is broke by the Higgs Mechanism
- Mechanism explains why $W^+$, $W^-$, and $Z^0$ have mass
- Predicts Higgs Boson as particle that does this
- Mass and few other properties generated by this mechanism create the rift
A little History

The foundations for this framework born at the end of 19th century

- 1895 – Radioactive decay discovered by Becquerel
- 1897 – J.J. Thomson discovers the electron
- 1900 – Planck’s idea of energy quantization
- 1905 – Einstein: Brownian motion suggests atoms (oh, photoelectric effect and relativity too)
- 1911 – Rutherford, using alpha particles demonstrates small, dense, positive nucleus
- 1913 – Bohr model of the atom
Theses accomplishments gave birth to other discoveries:

- **Spin** – deduced from Zeeman and Stark effects
- **Quantum theory:** matter as discrete wave packets, gives a more accurate view of the atom courtesy deBroglie, Schrödinger, Heisenberg, Dirac
Breakthroughs during the 1930s

- Quantum theory extended by Dirac to include relativity which gave rise to QED
- Neutron deduced from unaccounted for mass in nucleus, observed 1932
- Positron (antimatter) predicted by QED and found
- Muon found in Cosmic Ray Experiments!!
Enter the Weak Force

- Enrico Fermi – postulates weak force to explain beta decay

- Hans Bethe – sun and other stars burn through reverse beta decay, i.e. via the weak force
Other Breakthroughs of the 1930s

- Yukawa’s hypothesis of strong nuclear force – template for later theories of the standard model (also predicts pion)

- Wolfgang Pauli predicts neutrino to preserve energy conservation in beta decay

And then....
Particle Explosion!

The 40s, 50s, early 60s

- Particle explosion begins, many new particles discovered (lambda, kaon, pion, etc...)
- Property of strangeness observed
- Electron neutrino and then muon neutrino found as well
- Post WWII – SLAC evidence that protons are composite
Quarks!!

- 1964 – Breakthrough: Murray Gell-Mann and George Zweig independently put forward quark model

- Three quark model put forth with the 3 flavors, up, down, and strange

- SLAC sees evidence, but model still isn’t accepted
More quarks?

- Fourth quark predicted out of symmetry
  - There are four leptons, but only three quarks
- 1974 – BNL and SLAC both observe the Charm (# 4) quark, quark model finally excepted
- 1978 – Bottom quark (# 5) found, Top quark predicted
- 1970s – QCD formed to explain strong force, gluon predicted!
- 1994 – Top Quark (# 6) found!
Shedding Light on the Weak Force

1960s – Finally some understanding

- Glashow, Weinberg, and Salam put forth electroweak theory which…

  - Describes the weak force in terms of quantum theory and relativity
  - Describes the weak and electromagnetic force as two components of one electroweak force
  - Predicts $W^+$, $W^-$, and $Z^0$ as transmitters of the weak force
  - Implies Higgs Boson as a way to give Ws and Z mass
The Last Round up...

- **1977** – Tau lepton observed suggesting a third generation of quarks too
- **1983** – $W^+$ & $W^-$ bosons found
- **1984** – $Z^0$ boson found
  
  (note:  
  boson = particle of integer spin  
  while  
  fermion = half integer spin)
- **2000** – Tau neutrino found