The Standard Model

Physics, Not Taxonomy

Jesse Chvojka
University of Rochester
PARTICLE Program
A quick look

These are the ingredients you need to make our world minus a few of the details
Is this the Standard Model?

- Yes… and No, the Standard Model is more than just a list of particle, but what is it?
Let’s look at what it is...

- Description of the fundamental particles
- Description of three of the fundamental forces
  - Strong
  - Weak
  - Electromagnetic
- Union of weak & electromagnetic as the electroweak force
- Conservation laws, e.g. matter-energy, momentum, charge, etc...
...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.
Our Toolbox

Concepts and Methods

- Spin
  - Bosons
  - Fermions
- Quantization
- Antimatter
- Conservation Laws
- Feynman Diagrams
  - Real Particles
  - Virtual particles
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
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
Quantization

- Energy, charge, spin, matter, etc. come in quantized amounts

Einstein (1905) – light quantized, thus the photon

Logical Conclusion

- Force carriers — quantization of a force
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
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
More on Feynman Diagrams

- 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**
So what are Real and Virtual Particles?

Real particles
- Can be observed directly or indirectly in experiment
- Satisfy the relativity equation
  \[ E^2 = p^2c^2 + m^2c^4 \]

Virtual particles
- Cannot be observed directly, represents intermediate stage of a process
- \( E^2 \neq p^2c^2 + m^2c^4 \) !!!
- Allowed by Heisenberg’s Uncertainty principle
  \[ \Delta p \Delta x \geq \hbar/2 \quad \text{or} \quad \Delta E \Delta t \geq \hbar/2 \]
The Four (or Three) Fundamental Forces

Gravity

Strong Force

Electromagnetism

Weak Force
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
Electromagnetism

- Mediated by photon exchange
- Described by QED
- Infinite Range: acts on astronomical and atomic scales, responsible for chemical properties
- Attractive or repulsive force that acts upon objects with electric charge
Strong Force

- Strongest force, but **quarks** are only fermions that it affects
- Force mediated by **gluons**
- Quarks and gluons have **color charge** which is analogous to electric charge, but with differences that we’ll explore

So how does color work?
Three types of color charge, Red, Green, Blue and associated anti-color

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)
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 Confinement!!!
As two quarks are separated, the energy used creates a lot of gluon-gluon activity. Until enough energy is present in the gluon interactions to produce another quark pair. So quarks can’t be separated. And increasing gluon-gluon activity is why the Strong force increases with distance.
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!!
Weak Force

- Responsible for decays of massive quarks and leptons into lighter particles
- Cause of $\beta$ – decay and fusion in the sun
- Short range force mediated by the massive $W^+$, $W^-$, and $Z^0$ bosons
- Only way of particles of one generation to change into another (not counting neutrino oscillation)
Electroweak force

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

So why do physicists think these two forces are related?
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!)
- $W$s, $Z$, 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 a particle that does this
- Mass and few other properties generated by this mechanism create the rift
Those are the Forces and Their Carriers

But what about the other particles?
Quarks

- Affected by
  - strong force
  - weak force
  - electromagnetism
  - gravity

- Fractional charge

- Fermions – have spin 1/2

- Three generations differing only by mass
Leptons

- Affected by
  - weak force
  - electromagnetism
  - gravity

- Charged Leptons – 3 copies
- Neutrinos – 3 copies
  - no charge
  - tiny mass

- Fermions –
  - have spin 1/2

- Three generations differing only by mass
Unsolved Mysteries

- Gravity
- Why three generations
- Standard Model can’t predict a particles mass, oops, Higgs?
- Matter/Anti-Matter asymmetry
- Dark Matter

These are some of the kinks in the Standard Model
The Horizon

- Supersymmetry
- String Theory
- Extra Dimensions
- Dark Matter
- Dark Energy
- Grand Unified Theories
A little History

The foundations for this framework born at the end of 19\textsuperscript{th} century

- 1895 – Radioactive decay discovered by Becquerel
- 1897 – J.J. Thomson discovers the \textit{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
History Marches On

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

- Three quark model put forth with the 3 flavors, up, down, and strange.
- SLAC sees evidence, but the 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