Brief Standard Model Overview

- The **Standard Model** (SM) is the theory of all subatomic physics that explains all known forces except gravity (which we can tack on)
  - It is a relativistic quantum field theory
  - Every predicted SM particle has been discovered (last one, Higgs boson was in 2012)
  - Describes constituents of matter plus electromagnetic, weak (nuclear), and strong (nuclear) forces
  - There are a few aspects of physics it does not explain but is very well tested otherwise
  - This class is an intro to the SM with a simplified explanation of how to calculate in it, touching on a few applications + extensions

- "Matter" = fermion fundamental particles (spin = odd multiple of $\frac{1}{2}$, obeys Pauli exclusion)
  - Matter comes in 3 families or generations, each about the same as the previous but heavier
  - Leptons ("light")
    - Do not experience the strong force
    - Each family has a charged lepton (e^-, μ^-, τ^-) [electron, muon, tau], a neutrino (ν_e, ν_μ, ν_τ), and antiparticles (e^+, μ^+, τ^+, $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$)
    - Neutrinos have no charge $\Rightarrow$ no EM interaction. In the SM, they are massless
    - Each family experiences the weak force

- Quarks experience all forces
  - Each family has a quark with electric charge +2/3 (up, charm, top/truth = u, c, t) ← units of proton charge
    one w/ charge −1/3 (down, strange, bottom/beauty = d, s, b)
    and antiquarks

  - Each quark has one of 3 colors (red, green, blue = R, G, B) corresponding to "strong force charge," so really there are 18 quarks. Antiquarks have anticolors ($\bar{R}, \bar{G}, \bar{B}$)

  - Each family (u, d; c, s; t, b) interacts with weak force

  - Quarks are confined meaning we cannot free a quark. Instead they are always found in bound states called hadrons

    + Mesons ("medium") are made of a quark and antiquark pair. Include π, etc

    + Baryons ("heavy") are made of 3 quarks (R + G + B). Include protons, neutrons, etc

    + There is also now good evidence for "tetraquarks" and "pentaquarks" but the structure is still not well determined

◎ Force Carriers = boson fundamental particles (integer spin)

- Electromagnetism is carried by photons (γ) = quanta of EM fields. Massless

- The weak force is carried by $W^{\pm}$ and Z^0 particles

- Notice that $W^\pm$ have electric charge
  + They interact with photons, Z^0 is neutral.
  + A sign of <u>electroweak unification</u>
- These are massive ⟹ weak force is short range
  + By "energy-time uncertainty" virtual particles exist for a time $\Delta t \sim \hbar/\Delta E \sim \hbar/Mc^2$
  + So they can only travel a distance $c\Delta t \sim \hbar/Mc$
    This is the Compton wavelength of the particle

- <u>Gluons</u> (g) carry the strong force

  - There are 8 gluons, each with a color and anticolor ie $R/\bar{G}$, $B/\bar{R}$, etc. Not 9 due to "technicality"

  - Massless but confined like quarks b/c they interact with each other. But electrically neutral.

- <u>Higgs boson</u> is unique (spin 0) b/c it has an expectation value. It is responsible for
  - Separation of EM and weak forces
  - The mass of $W^\pm$, Z^0, leptons, and quarks (but <u>not</u> most of the mass of hadrons)

Beyond Standard Model (BSM) physics

- Neutrino Oscillation + Mass
  - We observe neutrinos change flavor $\nu_e \to \nu_\mu$, etc
    + In QM, this means there are mass differences
    + Technically not SM, but well accepted that ν have small masses
  - Question is how to incorporate the mass
  - We'll see oscillation of SM particles too

- Baryogenesis/leptogenesis: how/why is there matter but not antimatter?

- Dark matter
  - Convincing evidence of new particles due to invisible mass in universe
  - New heavy particle (WIMP), new light particle (axion), small black holes?

- Quantization of gravity, etc

Units

- You are familiar with SI units with physical constants like $\hbar$, c, ϵ_0.

- There is a choice of how to define charge that changes ϵ_0

  - Gaussian units set $\epsilon_0 = 1/4\pi$, so Coulomb's law $\vec{F} = q_1 q_2 / r^2 \, \hat{r}$
    + Commonly used in astrophysics
    + Textbook uses these.
    + "cgs" system is Gaussian

  - Heaviside-Lorentz sets $\epsilon_0 = 1 \Rightarrow$ Coulomb's law $\vec{F} = \frac{q_1 q_2}{4\pi r^2} \hat{r}$
    + Common in particle physics
    + My notes use these

- But $\hbar$ and c have dimensions. We will choose (in notes) units to set $\hbar = c = 1$. Natural units (and HL for EM)
  - In natural units $[L] = [T] = [m]^{-1} = [p]^{-1} = [E]^{-1}$
    + We only need to choose one unit.
    + In particle physics, use eV = electron-Volts
      = energy gained by electron moving through 1 Volt

  - To convert to SI (or whatever), replace factors of $\hbar$ and c as needed for dimensional analysis
  - Unless specified, you may use natural, SI, or cgs units when numbers are required.