Lecture 22

Way Beyond the Standard Model

Particle Detectors
Dynamical symmetry breaking, the Higgs Mechanism

- **Weinberg, Glashow & Salam (UNIFICATION OF EM and WEAK)**
  - Basic theory has 4 *massless* bosons: triplet $W_1, W_2, W_3$, and singlet $B$
  - Dynamical Symmetry Breaking via the Higgs Mechanism
  - $W_1, W_2$ become $W^\pm$, but $W_3$, and $B$ mix with “Weinberg angle” = $\theta_W$

$$
\begin{align*}
\gamma &= B^0 \cos \theta_W + W_3 \sin \theta_W \\
Z^0 &= -B^0 \sin \theta_W + W_3 \cos \theta_W
\end{align*}
$$

- $W$ and $Z$ masses are related
  $$m_W/m_Z = \cos \theta_W$$
- $\theta_W$ measured in neutrino scattering
  $$\sin^2 \theta_W = 0.233$$
- Predict: $m_W/m_Z = 0.88$ $m_W/m_Z = 80.4/91.2 = 0.88$

- **Simplest dynamical symmetry breaking would have 1 Higgs scalar (spin 0) particle**
  $$H^0$$
  $$200 \text{ GeV} > m_H > 115 \text{ GeV}$$
  experimental limit
Grand Unified Theory (GUT)

- At very high energies everything would be highly symmetric
- All masses and couplings would be the same
- At low energies the symmetry is broken

EW group is SU(2)×U(1): 4 gauge bosons (γ, W⁺, W⁻, Z)
QCD group is SU(3)\(_{\text{color}}\): 8 gauge bosons (gluons)
Simplest GUT is SU(5): \(\rightarrow 24\) gauge bosons (12 more bosons)
What about Gravity!
SU(5) has 12 more gauge particles

- Three with charge =-1/3, in three “colors” \((Y_R, Y_G, Y_B)\)
- Three with charge =-4/3, in three “colors” \((X_R, X_G, X_B)\)
- Six anti-particles of these

- These gauge particles can change quarks into leptons or change quarks into antiquarks
  
  Examples

- Can lead to proton decay (lifetime is < \(6 \times 10^{30}\) years) \(\text{N.G.}\)

- Some success. But no proton decay, no 3 generations, has monopoles
Supersymmetry (SUSY)

- Every fermion has a supersymmetric boson partner and vice-versa
  - electron (e) ---> selectron (\(\tilde{e}\))
  - quark (q) ---> squark (\(\tilde{q}\))
  - photon (\(\gamma\)) ---> photino (\(\tilde{\gamma}\))
  - gluon (g) ---> gluino (\(\tilde{g}\))
  - W,Z ---> wino (\(\tilde{W}\)), zino (\(\tilde{Z}\))
  - Higgs (H) ---> Higgsino (\(\tilde{H}\))
  - Higgs* (\(H^\pm\)) ---> Higgsino*(\(\tilde{H}^\pm\))

- R-parity  
  - R=+1 (particles)  R=-1 (supersymmetric particles)
- R-parity product conserved
  - supersymmetric particles produced in pairs (\(A + B \rightarrow \tilde{A} + \tilde{B}\))
    \((1 \times 1 = -1 \times -1)\)
  - Heavy supersymmetric particles decays (\(\tilde{A} \rightarrow \tilde{B} + A\))
    \((-1 = -1 \times +1)\)
  - Lightest supersymmetric particle cannot decay (might be stop quark)
  - Good Dark Matter candidate
Other qualities of Supersymmetry (SUSY)

• SUSY partners can cancel infinities that arise in calculations
• Unifies fermions an bosons
• Involves angular momentum inherently
  - rotational symmetries --- space translations
  - geometry of spacetime --- GRAVITY

• One major problem -- NOT a shred of evidence for it.
• Mass limit is greater than about 100 GeV
• Still looking at Fermilab Tevatron collider (CDF and D-Zero)
• Will look for it at LHC
Theories of everything

Everything's gone downhill since 1964.

Everything is my fault.

Everything is your fault.

Everything would be perfect if I had a dirt bike.
The Planck scale

- Fundamental constants
  \[ G = 6.7 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2} \]
  \[ \hbar = 1.05 \times 10^{-34} \text{ m}^2 \text{ kg s}^{-1} \]
  \[ c = 3 \times 10^8 \text{ m s}^{-1} \]

- Only one combination with \( G \) gives a length (The Planck Length)
  \[ L_p = \sqrt{G \hbar / c^3} = 1.6 \times 10^{-35} \text{ m} \]

- Combine again to get energy or mass, (The Planck Mass)
  \[ \hbar c / L_p = 1.2 \times 10^{19} \text{ GeV} \]

- GUT scale was \( 10^{15} \text{ GeV} \) (Did not include gravity)

- Quantum Gravity
  - exchange spin 2, massless gravitons, gives an attractive force
  - scattering cross sections give infinities
  - gravitino (spin 3/2) helps to cancel these out
  - still lots of problems that are not solved
String Theory

- Fundamental particles appear point-like
- Point-like particles give infinities
- String theory postulates particles have a size and have string-like properties
  - Theory is formulated in 10 (or more) dimensions
  - Based on 1920’s work by Kaluza & Klein
  - Particles can be closed or open strings
  - All extra dimensions except 3 space and 1 time are curled up
Why is String Theory so popular?

Table 1.

<table>
<thead>
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<th>QUESTION</th>
<th>SM</th>
<th>SSM</th>
<th>String Theory</th>
<th>Other</th>
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<td>what is matter</td>
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<td>what is light</td>
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Stay tuned

• The direction these theories will take is driven by Experiments
  - Fermilab/Japan Neutrino Oscillations (CP violation in leptons?)
  - Proton decay (decay modes involving K mesons)
  - Dark matter searches (nuclear recoils in cryo liquids )
  - Tevatron collider (Higgs, supersymmetry, CP violation, etc.)
  - Large Hadron Collider (ATLAS & CMS at 14 TeV)
  - International Linear Collider (the cleanest way to look)

• Next part of the course explains the operation of particle detectors and accelerators that are needed do these experiments.

• Materials Physics (Condensed Matter, Solid State, ...) plays a large role in understanding detectors and accelerators.
How to detect particles

- Particles are detected by making them ionize atoms!
- Detecting charged particles
  - The electric field of a moving charged particle can ionize the atoms of the material in which it moves.
  - Ionization electrons are small and low mass, and can be collected by an electric field. Positive ions are big and heavy, and sluggish.
  - A charged particle accelerated by a magnetic or electric field radiates photons that can ionize atoms and release electrons
- Detecting neutral particles
  - Interact the neutral particle with matter and in the process release ionization electrons.
  - Sometimes you must completely destroy the neutral particle, but its energy has been used to create ionization.
- Must study Ionization to understand detectors
Ionization

- Ionization potential minimum energy to ionize (outer e shell)
  - Hydrogen 13.5 eV
  - Helium 25 eV
  - Lithium 5 eV
  - Neon 22 eV

- Average ionization potential, includes inner shells
  - reaction dependent
  - for charged particles (e.g., electrons)
    - $\sim 16Z^{0.9}$ (eV) for $Z>1$
    - Low Z Nobel Gases (He, Ne, Ar, a little higher)
Photon induced ionization

- **Photon (<20 eV) induced**
  - Only valence electrons (a few)
  - Non-penetrating
  - Gases & surfaces
    - high temperature
      - thermionic emission
    - high electric fields
    - ultraviolet light
      - photoelectric effect
      - ozone
    - photo-cathodes (Cs)
    - silicon photodiodes

- **X-ray (<1 MeV) induced**
  - All electrons (Z)
  - Penetrating
  - Gases & solid interiors

- **Useful conversion**
  \[ \lambda \text{– wavelength, } \nu \text{– frequency} \]
  \[ hc = 2\pi \left( \frac{hc}{c} \right) = 2\pi \left( 200 \text{ MeV} \cdot \text{fm} \right) = 1.2 \times 10^3 (\text{eV} \cdot \text{nm}) \]

- **Photon energies**
  \[ E = h\nu = \frac{hc}{\lambda} = \frac{1200 (\text{eV} \cdot \text{nm})}{\lambda} \]