Scalar Dark Matter from Grand Unified Theories

T. Daniel Brennan

November 24, 2014
1. Standard Model
2. Dark Matter
3. GUTs
4. Babu-Mohapatra Model
5. Conclusions
Gauge theory that explains strong weak, and electromagnetic forces

\[ SU(3)_C \times SU(2)_W \times U(1)_Y \]

Each generation (3) has 2 quark flavors (each comes in one of three colors) and 2 leptons

- Each type of quark and lepton can have either left or right chirality except the neutrino
- Each left pair forms a doublet which transforms under SU(2) (couples to the weak force)
- Each quark flavor forms a triplet which transforms under SU(3) (couples to strong force)

There is also a Higgs boson doublet (which transforms under SU(2))

\[ Y = 2(Q - l_3) \]
Scalar Dark Matter from Grand Unified Theories

What is the Standard Model?
Standard Model
Mathematics of the Standard Model

- **Standard Model Multiplets**

\[ Q^{(c)}|_L = \left( \begin{array}{c} u^{(c)} \\ d^{(c)} \end{array} \right)_L \quad E_L = \left( \begin{array}{c} \nu_e \\ e^- \end{array} \right)_L \quad \phi = \frac{1}{\sqrt{2}} \left( \begin{array}{c} \phi^+ \\ \phi^0 \end{array} \right) \]

\[ u^{(c)}_R \quad d^{(c)}_R \quad e^-_R \]

- **Standard Model Lagrangian**

\[ \mathcal{L} = \bar{Q}_L (i\partial_\mu \phi + g_W \sigma^A W^A + g_S T^A G^A + \frac{g_Y}{3} A) Q_L \]
\[ + \bar{E}_L (i\partial_\mu \phi + g_W \sigma^A W^A - g_Y A) E_L + \ldots \]
\[ + \frac{1}{2} \left| \left( \partial_\mu + ig_W \sigma^A W^A_\mu + ig_Y A_\mu \right) \phi \right|^2 \]
\[ - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} + \ldots + \mathcal{L}_{Yukawa} + V(\phi) \]
At observable energies, the standard model breaks to $SU(3)_C \times U(1)_{EM}$.

At some energy level (standard model breaks around 246 GeV) Higgs boson gains value expectation value

- Reparametrize $\phi = \nu + \sigma$
Standard Model
Results of Electroweak Symmetry Breaking

After Electroweak Symmetry Breaking:

- Weak force propagators gain mass (part that breaks symmetry)
- Higgs boson mass changes
- Mass of particles coupled to Higgs boson by Yukawa term change
In the effective action of QFT, gauge couplings have quantum corrections given by higher order processes.

In renormalizing the gauge couplings, introduce a parameter $\mu$ (renormalization scale) with dimensions of energy. It describes how couplings change with energy scale of interactions.
Standard Model
Problems with the Standard Model

- No quantum description of gravity
- Matter/anti-matter asymmetry
- Neutrino Mass
- Landau Pole
- Strong CP Problem
- Hierarchy Problem-Cancellation of quantum corrections to Higgs mass
- L-R Asymmetry/Irreducible representation of gauge group
- Gauge group structure unexplained
- Dark Matter
Dark Matter
What is Dark Matter?

- Cold
  - Non-relativistic at some comparable era of the universe
  - Hot dark matter smooths out over density fluctuations
    \( \sim 1 \text{keV} \)
- Collisionless
  - No scatters on average \( \Rightarrow n\sigma vT_{univ} \approx 1 \) or
    \[ \frac{\sigma}{10^{-24} \text{cm}} \leq \frac{1 \text{TeV}}{M_{DM}} \]
- Dark
  - Does not couple to Photons
- Matter
  - \( u_{DM} \sim T^{3(1+w)} \) with \( w \approx 0 \)
Dark Matter
Evidence

- Rotation Curves

- CMB
  - Fluctuation density not enough to form structure

- Gravitational Lensing
  - Bullet Cluster
Interacts through Gravity ⇒ Massive
  Makes up ∼ 85% of matter in Universe

Is non-luminous ⇒ neutral charge

Does not react very much with normal baryonic matter ⇒ unlikely to interact through the strong force

WIMPs (Weakly Interacting Massive Particles) are an obvious choice for candidates
WIMPs are theorized to have been created in their current abundance by Thermal Relic model

- Characteristic length scale of universe $a \sim T^{-1}$
- $n_{rel} \sim T^3$
- $n_{non-rel} \sim T^{3/2} e^{-m_X/T}$
- $n = \int \frac{d^3p}{e^{E(p)/T} \pm 1}$
Panoply of theories attempt to model dark matter observations. Several popular theories include:

- **Neutralino - Supersymmetry**
  - Combination of photino, zino, and neutral higgsino
  - Protected by R-Symmetry - lightest supersymmetric particle (LSP)

- **Axion - Solution to Strong CP Problem**
  \[ \mathcal{L}_{\text{Axion}} = \frac{g^2 \theta}{32 \pi^2} \epsilon_{\mu \nu \sigma \rho} G^a_{\mu \nu} G^a_{\sigma \rho} = \frac{g^2 \theta}{32 \pi^2} \tilde{G}_{\mu \nu} G^{\mu \nu} \]

- **Sterile Neutrino - Giving up on life**
  - Neutral leptons which only couple to gravity
Dark Matter
Experiments

- **Particle Accelerator Searches**
  - **LHC**
    - Look for missing energy/momentum in measurements

- **Direct Detection**
  - **Large Underground Xenon experiment (LUX)**
    - Detect photons and electrons $\Rightarrow$ electroluminescence
Dark Matter
Experiments

Scalar Dark Matter from Grand Unified Theories
T. Daniel Brennan

Standard Model
Dark Matter
GUTs
Babu-Mohapatra Model
Conclusions
Grand Unified Theories (GUTs) extend standard model to a larger semisimple gauge group with single fundamental force by using spontaneous symmetry breaking as in electroweak symmetry breaking. Can be used to explain

- Matter/antimatter asymmetry
- Neutrino Mass
- L-R Asymmetry/Irreducible representation of gauge group
- Landau Pole
- Dark Matter???

Common GUTs are SU(5) and SO(10)

GUTs predict Proton Decay
To extend the standard model to a larger gauge group, need to add new scalar higgs multiplet to break gauge group down to standard model.

Common Higgs multiplets are 5, 10, 16, 45, 54, 126, 144, 210 dimensional.
Neutrino Mass

Suppressed Proton Decay

L-R Symmetry

Irreducible Representation

As few symmetry breaking steps as possible

Suggests SO(10) model containing $10 \oplus 126 \oplus$? Higgs sector. Also want to try to incorporate Dark Matter candidates
### Decomposition of a couple Higgs multiplets under various subgroups of SO(10)

<table>
<thead>
<tr>
<th>4c 2L 2R</th>
<th>4c 2L 1R</th>
<th>3c 2L 2R 1BL</th>
<th>3c 2L 1R 1BL</th>
<th>3c 2L 1Y</th>
<th>51Z</th>
<th>5' 1Z'</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1,1,3)</td>
<td>(1,1,0)</td>
<td>(1,1,0)</td>
<td>(1,1,+1)</td>
<td>(1,1,+1)</td>
<td>(10,-4)</td>
<td>(10, +4)</td>
</tr>
<tr>
<td>(1,1,-1)</td>
<td>(1,1,-1)</td>
<td>(1,1,-1)</td>
<td>(1,1,-1)</td>
<td>(1,1,-1)</td>
<td>(10, -4)</td>
<td>(10, -4)</td>
</tr>
<tr>
<td>(1,3,1)</td>
<td>(1,3,0)</td>
<td>(1,3,0)</td>
<td>(1,3,0)</td>
<td>(1,3,0)</td>
<td>(24,0)</td>
<td>(24,0)</td>
</tr>
<tr>
<td>(6,2,2)</td>
<td>(3,2,2,-1/2)</td>
<td>(3,2,2,-1/2)</td>
<td>(3,2,2,-1/2)</td>
<td>(3,2,2,-1/2)</td>
<td>(10, -4)</td>
<td>(24,0)</td>
</tr>
<tr>
<td></td>
<td>(6,2,-1/2)</td>
<td>(3,2,2,-1/2)</td>
<td>(3,2,2,-1/2)</td>
<td>(3,2,2,-1/2)</td>
<td>(24,0)</td>
<td>(10, -4)</td>
</tr>
<tr>
<td>(15,1,1)</td>
<td>(1,1,0)</td>
<td>(1,1,0)</td>
<td>(1,1,0)</td>
<td>(1,1,0)</td>
<td>(24,0)</td>
<td>(24,0)</td>
</tr>
<tr>
<td>(3,1,1,+1/2)</td>
<td>(3,1,0,+1/2)</td>
<td>(3,1,1,+1/2)</td>
<td>(3,1,0,+1/2)</td>
<td>(3,1,1,+1/2)</td>
<td>(10, -4)</td>
<td>(10, -4)</td>
</tr>
<tr>
<td>(3,1,1,-1/2)</td>
<td>(3,1,0,-1/2)</td>
<td>(3,1,1,-1/2)</td>
<td>(3,1,0,-1/2)</td>
<td>(3,1,1,-1/2)</td>
<td>(24,0)</td>
<td>(24,0)</td>
</tr>
<tr>
<td>(8,1,1,0)</td>
<td>(8,1,0,0)</td>
<td>(8,1,0,0)</td>
<td>(8,1,0,0)</td>
<td>(8,1,0,0)</td>
<td>(24,0)</td>
<td>(24,0)</td>
</tr>
</tbody>
</table>
Babu-Mohapatra Model
Specifics

- Single step symmetry breaking $M_U \approx 10^{15.5}$ GeV
  - Higgs Sector $10 \oplus 45 \oplus \overline{45} \oplus 126$
  - Produces Seesaw mechanism which gives proper neutrino mass and mixing

- Highly suppressed Proton Decay
  - Lifetime on order of $10^{34} - 10^{35}$ years
  - Current limit from Super-Kamiokande is $5.9 \times 10^{33}$ years
  - Currently working on calculating to 2-loop order

- At low energies, has color sextet and 2 identical weak triplets which transform under SM as $(6, 1, 2/3)$ and $(1, 3, 0)$ respectively
  - Mass scale approx 1-10 TeV
2006 Cirelli, Fornengo, and Strumia characterized scalar and fermionic 2-4 WIMP multiplets. First order approximation to this model.

<table>
<thead>
<tr>
<th>Quantum numbers</th>
<th>DM can decay into</th>
<th>DM mass in TeV</th>
<th>$m_{\text{DM}} - m_{\text{DM}}$ in MeV</th>
<th>Events at LHC $\int \mathcal{L} dt = 100$/fb</th>
<th>$\sigma_{\text{SI}}$ in $10^{-45}$ cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU(2)$_L$ U(1)$_Y$ Spin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 1/2 0</td>
<td>$EL$</td>
<td>0.54 ± 0.01</td>
<td>350</td>
<td>320–510</td>
<td>0.3</td>
</tr>
<tr>
<td>2 1/2 1/2</td>
<td>$EH$</td>
<td>1.2 ± 0.03</td>
<td>341</td>
<td>150–300</td>
<td>0.3</td>
</tr>
<tr>
<td>3 0 0</td>
<td>$HH^*$</td>
<td>2.0 ± 0.05</td>
<td>166</td>
<td>0.2–1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>3 0 1/2</td>
<td>$LH$</td>
<td>2.5 ± 0.06</td>
<td>166</td>
<td>0.7–3.5</td>
<td>1.3</td>
</tr>
<tr>
<td>3 1 0</td>
<td>$HH, LL$</td>
<td>1.6 ± 0.04</td>
<td>540</td>
<td>3.0–10</td>
<td>2.5</td>
</tr>
<tr>
<td>3 1 1/2</td>
<td>$LH$</td>
<td>1.9 ± 0.05</td>
<td>526</td>
<td>25–80</td>
<td>2.5</td>
</tr>
<tr>
<td>4 1/2 0</td>
<td>$HHH^*$</td>
<td>2.4 ± 0.06</td>
<td>353</td>
<td>0.10–0.6</td>
<td>1.9</td>
</tr>
<tr>
<td>4 1/2 1/2</td>
<td>$LHH^*$</td>
<td>2.4 ± 0.06</td>
<td>347</td>
<td>4.8–23</td>
<td>1.9</td>
</tr>
<tr>
<td>4 3/2 0</td>
<td>$HHH$</td>
<td>2.9 ± 0.07</td>
<td>729</td>
<td>0.01–0.10</td>
<td>10</td>
</tr>
<tr>
<td>4 3/2 1/2</td>
<td>$LHH$</td>
<td>2.6 ± 0.07</td>
<td>712</td>
<td>1.5–8.7</td>
<td>10</td>
</tr>
<tr>
<td>5 0 0</td>
<td>$(HHH^<em>H^</em>)$</td>
<td>5.0 ± 0.1</td>
<td>166</td>
<td>$\ll 1$</td>
<td>12</td>
</tr>
<tr>
<td>5 0 1/2</td>
<td>–</td>
<td>4.4 ± 0.1</td>
<td>166</td>
<td>$\ll 1$</td>
<td>12</td>
</tr>
<tr>
<td>7 0 0</td>
<td>–</td>
<td>8.5 ± 0.2</td>
<td>166</td>
<td>$\ll 1$</td>
<td>46</td>
</tr>
</tbody>
</table>

Total LHC Luminosity:

$$44.2 \text{ pb}^{-1} + 6.1 \text{ fb}^{-1} + 23.3 \text{ fb}^{-1} = 29.4 \text{ fb}^{-1}$$
Babu-Mohapatra Model

Dark Matter Observations

LUX data from Feb 2014

$$\sigma_{SI} \approx 1.3 \times 10^{-45} \text{ cm}^2$$
To complete the first order approximation need to check to make sure mass fits observation. Used to fix unification scale:

- $M_\omega = 2$ TeV
- $M_\Delta = 12$ TeV
- $M_U \approx 10^{15.2}$ GeV
Conclusions
Future Directions and Applicability

- **Future Directions**
  - Calculate Proton decay rate to 2-loop
  - Verify Stability
  - Formulate dynamical thermal relic model
  - Look for observable effects

- **Applicability**
  - Provides a newly motivated theory of dark matter
  - Will rule out or provide strong constraints on GUTs
Proton Decay

Given:

\[
\begin{align*}
\psi_0 &= \nu^c_L \\
\bar{\psi}_i &= \begin{pmatrix} d^c_1 \\ d^c_2 \\ d^c_3 \\ e^- \\ \nu \end{pmatrix}_L \\
\psi_{ij} &= \begin{pmatrix} 0 & u^c_3 & -u^c_2 & u_1 & d_1 \\ 0 & u^c_1 & u_2 & d_2 \\ 0 & u_3 & d_3 \\ 0 & e^+ \end{pmatrix}_L
\end{align*}
\]

the gauge bosons couple \(\psi_0\) to \(\psi_{ij}\) and \(\psi_{ij}\) to \(\epsilon_{ijklm}\psi_k\) and \(\psi_{ij}\) to either \(\psi_{ik}\) or \(\psi_{kj}\).

So we can have a boson X which takes \(d_3 \rightarrow X + e^+\) and \(u_2 + X \rightarrow u^c_1\). This takes \(p \rightarrow \pi^0 e^+\).