LHC Implication Of Grand unification

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The concept that matter is composed of discrete units and cannot be divided into arbitrarily tiny quantities has been around for millennia.

Empedocles, 490–430 BC
Scale in m:

$10^{-10}$ m

$10^{-14}$ m

$10^{-15}$ m

$\leq 10^{-18}$ m

Scale in $10^{-18}$ m:

100,000,000

10,000

1,000

$\leq 1$
$45 + 12 + 1$
4 vs 58?
Unification and predictions

String Theory

Grand Unification

SUSY?

Quantum Gravity

Super Unification

Electroweak Model

Standard model

Electroweak Weak Theory

QED

Electromagnetism

Maxwell

Weak Force

Magnetism

Long range

Electricity

Fermi

Weak Force

Nuclear Force

Short range

Quantum

Universal Gravitation

Einstein, Newton

Terrestrial Gravity

Kepler

Celestial Gravity

Long range

Galilei

Gravity
The Standard Model is the theory governing fundamental particles and interaction (except Gravity)

For $L \geq 10^{-18} \text{ m}$ $\iff E \leq 10^2 \text{ GeV}$

SM is the Theory of Forces & the Particles

$\text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y$

8 Gluons $\quad W^\pm, W^0$ $\quad B$

Spin 1 bosons
Particles are ``Chiral Fermions''

It is more convenient to work in left (or right) handed bases

We can just drop all “L” subscripts and write all field in terms of left-handed components

\[
Q: \quad (3, 2, 1/6) \\
L: \quad (1, 2, -1/2) \\
\ell^c: \quad (\bar{3}, 1, -2/3) \\
d^c: \quad (\bar{3}, 1, 1/3) \\
e^c: \quad (1, 1, 1)
\]

\[
Q_L = \left(3, 2, \frac{1}{6}\right), \quad \text{but} \quad NOT \quad \left(\bar{3}, 2, -\frac{1}{6}\right)
\]
The conjugate of a right-handed component of a fermion is the left-handed component of the conjugate fermion!

Recall ``charge conjugate” operation (particle ↔ antiparticle)

\[
\Psi^c \equiv i \gamma^2 \Psi^* \\
(\Psi_R)^c = i \gamma^2 \left( \frac{1}{2} (1 + \gamma_5)\Psi \right)^* \\
= \frac{i}{2} \gamma^2 (1 + \gamma_5)\Psi^* \\
= \frac{1}{2} (1 - \gamma_5)[i\gamma^2\Psi^*] \\
= (\Psi^c)_L
\]
The SM Higgs sector

\[ \text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y \]

\[ \langle \varphi \rangle \quad \text{Higgs VEV} \]

\[ \text{SU}(2)_L \]

\( \varphi \) — Higgs field is \( \text{SU}(2)_L \) doublet, complex scalar field

\[ \varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}_{y=1/2} \]

Four degree of freedom
Yukawa sector

$$L = Y_d \bar{Q}_L \varphi \ d_R + Y_u \bar{Q}_L (i \tau_2 \varphi^*) u_R + Y_e L_L \varphi \ e_R + h. \ c.$$ 

The fermions gain masses

$$m_i = Y_i < \varphi > = \frac{Y_i v}{\sqrt{2}}$$

We have three generation quarks and leptons.

We have mixing between generation.
Chiral Adler-Bell-Jackiw (ABJ) anomaly

The ABJ anomaly spoils the renormalizability of a gauge theory.

Figure 20.2. Possible gauge anomalies of weak interaction theory. All of these anomalies must vanish for the Glashow-Weinberg-Salam theory to be consistent.
Miraculous Cancellation of Anomalies

- $SU(3)_C^2 \times U(1)_Y$: $\frac{1}{2} \left[ 2 \times \left( \frac{1}{6} \right) + 1 \times \left( -\frac{2}{3} \right) + 1 \times \left( \frac{1}{3} \right) \right] = 0$

- $SU(2)_L^2 \times U(1)_Y$: $\frac{1}{2} \left[ 3 \times \left( \frac{1}{6} \right) + 1 \times \left( -\frac{1}{2} \right) \right] = 0$

- $(\text{gravity})^2 \times U(1)_Y$:
  \[
  \left[ 3 \times 2 \times \left( \frac{1}{6} \right) + 3 \times \left( -\frac{2}{3} \right) + 3 \times \left( \frac{1}{3} \right) + 2 \times \left( -\frac{1}{2} \right) + 1 \times 1 \right] = 0
  \]

- $U(1)_Y^3$:
  \[
  \left[ 3 \times 2 \times \left( \frac{1}{6} \right)^3 + 3 \times \left( -\frac{2}{3} \right)^3 + 3 \times \left( \frac{1}{3} \right)^3 + 2 \times \left( -\frac{1}{2} \right)^3 + 1 \times (1)^3 \right] = 0
  \]

Relative $Y$-values are fixed \hspace{1cm} \rightarrow \hspace{1cm} \text{charge quantization}

But overall normalization still is not fixed
The SM - Things to remember

1) Lots of seemingly disconnected representations for gauge & particle content

2) 3 independent gauge couplings: \((g_1, g_2, g_Y)\)

3) Yukawa sector is unconstrained.

4) Particle representations are chiral

\[ Q_L = \left( 3, 2, \frac{1}{6} \right), \quad \text{but} \quad \text{NOT} \quad \left( \bar{3}, 2, -\frac{1}{6} \right) \]
5) Overall normalization for hypercharge unfixed, (since $U(1)_Y$ Abelian), Even thought relative $Y$-values are fixed
6) Higgs mechanism breaks

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

In general, the subgroup which survives is the subgroup with respect the field getting the non zero VEV is neutral
7) In SM

- Baryon # (B) conserved
- Lepton # (L) conserved

Thus, proton is stable!

Note: $B$ – is actually broken by instanton effects (very small)
$L$ – can be broken by RH neutrino Majorama mass
The rank of The SM gauge symmetry

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$2 + 1 + 1 = 4$$

Our goal – to “unify” all of the forces and particles

We need a bigger group
What groups $G$ can we choose?

<table>
<thead>
<tr>
<th>SM has rank = 4</th>
<th>1. group $G$ must be rank $\geq 4$ and contain SM as subgroup</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM has chiral reps $(3, 2, 1/6)$ but not $(\bar{3}, 2, -1/6)$</td>
<td>Group $G$ must also have chiral reps</td>
</tr>
<tr>
<td>SM is free of chiral anomaly</td>
<td>Group $G$ must have reps for which chiral anomalies are canceled</td>
</tr>
<tr>
<td>If we want to relate the gauge couplings to each other</td>
<td>$G$ should be a simple group</td>
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## Classification of Lie Groups

<table>
<thead>
<tr>
<th>Rank 1</th>
<th>U(1), SU(2)</th>
<th>SO(3)</th>
<th>Sp(2)</th>
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<tbody>
<tr>
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<td>SU(3)</td>
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<td>Rank 3</td>
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<td>Sp(8)</td>
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<td>SO(11)</td>
<td>Sp(10)</td>
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<td>SO(13)</td>
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</table>
Does SU(5) symmetry have the potential for a successful unification?

SU(5) symmetry has the following representations:
1, 5, 10, 15, 24, 45, 50, 78 etc.

Recall each SM generation contains 15 states and 3 generations. \((3 \times 15 = 45)\)

\[
\text{SU}(5) \quad \rightarrow \quad \text{SU}(3) \times \text{SU}(2) \times \text{U}(1)
\]

\[
15 = (3,1)_6 + (2,3)_1 + (1,6)_{-4}
\]

\[
45 = (2,1)_3 + (1,3)_1 + (3,3)_{-2} + (1,3)_8 + (2,3)_{-7} + (1,6)_{-2} + (2,8)_3
\]

Here all U(1) charges are normalized to avoid fractions.
But let’s look at $\bar{5}$ and $10$ dimensional representation

$$\begin{align*}
\text{SU}(5) & \quad \longrightarrow \quad \text{SU}(3) \times \text{SU}(2) \times \text{U}(1) \\
\bar{5} &= (\bar{3},1)_{-2} + (1,2)_{-3} \\
10 &= (\bar{3},1)_{-4} + (3,2)_{1} + (1,1)_{6}
\end{align*}$$

we have to rescale $\text{U}(1)$ quantum numbers by $1/6$

$$10_{[\alpha\beta]} = (\bar{3}, 1)_{-\frac{2}{3}} + (3, 2)_{\frac{1}{6}} + (1, 1)_{1}$$

$$\bar{5} = (\bar{3},1)_{1/3} + (1,2)_{-1/2}$$
An Entire SM generation fits into: $\bar{5} + 10$

Nothing left over and no exotics!

Anomaly cancellation?

Since we have not added new exotic fermions, the anomaly cancelation still it is OK

$$\bar{5} : (d_1^c, d_2^c, d_3^c, e, -\nu_e)$$

$$10 : \frac{1}{\sqrt{2}} \begin{pmatrix}
0 & u_3^c & -u_2^c & u_1 & d_1 \\
-u_3^c & 0 & u_2^c & u_1 & d_2 \\
u_2^c & -u_1^c & 0 & u_3 & d_3 \\
-u_1 & -u_2 & -u_3 & 0 & e^c \\
d_1 & d_2 & d_3 & -e^c & 0
\end{pmatrix}$$
Gauge bosons

\[24 \rightarrow (8, 1)_0 + (1, 3)_0 + (1, 1)_0 + (3, 2)_{-5/6} + (\bar{3}, 2)_{5/6}\]

- gluinos \(A^\pm, A^0\)
- B
- X, Y bosons

All SM gauge bosons are successfully embedded.

X and Y gauge bosons carry both color and electroweak charges simultaneously!
They can connect quarks \(\leftrightarrow\) leptons!
They can also turn quark directly to antiquark!

![Diagram](image)
The current experimental limit is:

\[ \tau(p \to e^+ \pi^0) > 1.4 \times 10^{34} \text{yr} \]
Overall hypercharge $Y$ normalization finally fixed

$$\text{SU}(5) \quad \rightarrow \quad \text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$$

Hypercharge is one of the non-Abelian generator

$$Q_{EM} = T_3 + Y = T_3 + cT_0$$

$$Y(5) = \left( -\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{1}{2}, \frac{1}{2} \right)$$

$$T_0 = \frac{1}{\sqrt{60}}((2, 2, 2, -3, -3))$$

$$\bar{5} : (d_1^c, d_2^c, d_3^c, e, -\nu_e)$$

$$c = -\sqrt{\frac{3}{5}}$$

$$Y_{SU(5)} = \sqrt{\frac{3}{5}} Y_{SM}$$

$$[D_\mu = \partial_\mu + i\frac{g_Y Y}{2} B_\mu]$$

The product $(g_Y Y)$ must be preserved

$$g_Y^{SU5} = \sqrt{\frac{5}{3}} g_Y^{SM}$$
So, unification into a single GUT group such as SU(5) requires all generators to act with a common couplings

\[ g_5 \equiv \left( g_3 = g_2 = g_1 = \sqrt{\frac{5}{3}} \, g_Y \right) \]

\[ \alpha_5 \equiv (\alpha_3 = \alpha_2 = \alpha_1 = \frac{5}{3} \alpha_Y) \]

\[ \frac{g_3}{g_2} = 1 \]

\[ \sin^2 \theta_W = \frac{g_Y^2}{g_2^2 + g_Y^2} = \frac{3}{8} = 0.375 \]

But at electroweak scale we have

\[ \alpha_3^{-1} \approx 8.5 \]

\[ \alpha_2^{-1} \approx 29.6 \]

\[ \alpha_1^{-1} \approx 59.1 \]

- Couplings are not equal
- \( \sin^2 \theta_W \approx 0.23, \ NOT 0.375 \)
The Yukawa (mass) matrix for down quarks is just the transpose of the Yukawa (mass) matrix for the charge leptons.

Introduce a 45 rep as another new Higgs

\[
\begin{pmatrix}
\frac{m_e}{m_\mu} = \frac{m_d}{m_s} \\
\frac{m_e}{m_\tau} = \frac{1}{9} \frac{m_d}{m_s}
\end{pmatrix}
\]

Or consider effective non-renormalizable couplings

\[
Y'_5 5_f 10_f \left( \frac{\Sigma}{M} \right)^n 5^* 
\]
\[ 10 = u^c (3,1)_{-2/3} + Q (3,2)_{1/6} + e^c (1,1)_1 \]

\[ 10_f \ 10_f \ 5_H \quad \Rightarrow \quad Y_U = Y_U^T \]

The Yukawa (mass) matrix for the top quark is symmetric
Open Questions for the Standard Model

- Why local gauge $SU(3)_c \times SU(2)_L \times U(1)_Y$ interaction?
- Why $g_1 : g_2 : g_3 = 1 : 2 : 7$?
- Why electric charge is quantized
  \[ Q_p = Q_e \text{ to better than 1 part in } 10^{21} \]
- Why 3 families of quarks and leptons?
- What is origin of quark and lepton masses and mixing?
- How neutrino masses and mixing angles are generated?
- What is nature of dark matter?
- Strong CP problem?
Low Energy Supersymmetry

- Resolves the gauge hierarchy problem;
- Provides cold dark matter candidate (LSP);
- Implements radiative electroweak symmetry breaking;
- Predicts new particles accessible at the LHC;
- Improves unification of the SM gauge and Yukawa couplings.
• Improves unification of the SM gauge couplings.
b − τ Yukawa coupling unification ♡ SUSY
Finite SUSY threshold corrections

Dominant contributions to the bottom quark mass from the gluino and chargino loop

$$
\delta y_b \approx \frac{g_3^2}{12\pi^2} \frac{\mu m_g \tan \beta}{m_b^2} + \frac{y_t^2}{32\pi^2} \frac{\mu A_t \tan \beta}{m_t^2} + \ldots
$$

where $m_{\tilde{b}}$ and $m_{\tilde{t}}$ stands for sbottom and stop mass.

where $\lambda_b = y_b$ and $\lambda_t = y_t$
<table>
<thead>
<tr>
<th>SU(5)</th>
<th>SO(10)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fermion sector:</strong></td>
<td><strong>Fermions:</strong> $16_i$</td>
</tr>
<tr>
<td>$10_i + 5_i + (1_i ?)$</td>
<td>existence of $\nu_R$ and thus neutrino mass via seesaw mechanism</td>
</tr>
<tr>
<td><strong>SM Higgs:</strong></td>
<td><strong>SM Higgs:</strong></td>
</tr>
<tr>
<td>$\overline{5_H} + 5_H$</td>
<td>$10$</td>
</tr>
<tr>
<td><strong>$Z_2$ R-parity</strong></td>
<td><strong>Automatic $Z_2$ matter parity</strong></td>
</tr>
<tr>
<td>$10_f \overline{5_f} \overline{5_f}$</td>
<td>$16_f 16_f 16_f$</td>
</tr>
<tr>
<td>$\overline{5_H} + 5_H + 24$</td>
<td>$144 + \overline{144}$</td>
</tr>
</tbody>
</table>
Yukawa sector

$16_f \times 16_f \times 10_H$
SUSY SO(10) GUT with non universal gauginos

- $m_{16}, m_{10}, M_i, A_0, \tan \beta, \text{sign}(\mu)$

- $m_{16} \equiv$ Universal soft SUSY breaking (SSB) sfermion mass

- $m_{10} \equiv$ Universal SSB MSSM Higgs mass.

- $M_i \equiv$ SSB gaugino masses. $M_1 : M_2 : M_3 = 1 : 3 : -2$
  at $M_{GUT}$ comes from $\frac{F_{\Phi_{ab}}}{M_P} \chi^a \chi^b$

- $A_0 \equiv$ Universal SSB trilinear interaction

- $\tan \beta = \frac{v_u}{v_d}$

- $\mu \equiv$ SUSY bilinear Higgs parameter $\mu > 0$
We have performed random scans for the following parameter range

\[0 \leq m_{16} \leq 10 \text{ TeV}\]
\[0 \leq m_{10} \leq 10 \text{ TeV}\]
\[0 \leq m_1 \leq 5 \text{ TeV}\]
\[35 \leq \tan \beta \leq 55\]
\[-3 \leq \frac{A_0}{m_{16}} \leq 3\]

SUSY and $t - b - \tau$ Yukawa coupling unification
Finite SUSY threshold corrections

Dominant contributions to the bottom quark mass from the gluino and chargino loop

\[ \delta y_b \approx \frac{g_3^2}{12\pi^2} \frac{\mu m_{\tilde{g}} \tan \beta}{m_{\tilde{b}}^2} + \frac{y_t^2}{32\pi^2} \frac{\mu A_t \tan \beta}{m_t^2} + \ldots \]

where \( m_{\tilde{b}} \) and \( m_{\tilde{t}} \) stands for sbottom and stop mass.

where \( \lambda_b = y_b \) and \( \lambda_t = y_t \)
The Lightest CP Even Higgs Boson Mass in the MSSM

\[ m_h^2 \approx M_Z^2 \cos^2 2\beta \left( 1 - \frac{3}{8\pi^2} \frac{m_t^2}{v^2} t \right) + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[ \frac{1}{2} \tilde{X}_t + t \right. \\
+ \frac{1}{16\pi^2} \left( \frac{3}{2} \frac{m_t^2}{v^2} - 32\pi \alpha_3 \right) \left( \tilde{X}_t t + t^2 \right) \]

\[ t = \log \frac{M_{SUSY}^2}{m_t^2}, \quad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2} \left( 1 - \frac{X_t^2}{12M_{SUSY}^2} \right) \]

\[ X_t = A_t - \mu \cot \beta, \quad M_{SUSY} = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}} \]
Higgs mass from Yukawa coupling unification in SUSY

There is around 2 GeV theoretical error in the calculation of CP-even Higgs mass.

\[ m_h \approx 125.8 \pm 0.6 \text{ GeV (CMS)}, \quad m_h \approx 126 \pm 0.6 \text{ GeV (ATLAS)} \]
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<tbody>
<tr>
<td>(m_{10})</td>
<td>(4.19 \times 10^2)</td>
<td>(3.82 \times 10^3)</td>
<td>(4.49 \times 10^2)</td>
<td>(1.94 \times 10^3)</td>
</tr>
<tr>
<td>(m_{16})</td>
<td>(2.13 \times 10^3)</td>
<td>(2.69 \times 10^3)</td>
<td>(1.91 \times 10^3)</td>
<td>(2.00 \times 10^3)</td>
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<tr>
<td>(M_1)</td>
<td>(1.89 \times 10^3)</td>
<td>(2.00 \times 10^3)</td>
<td>(1.78 \times 10^3)</td>
<td>(1.51 \times 10^3)</td>
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<tr>
<td>(M_2)</td>
<td>(5.67 \times 10^3)</td>
<td>(6.00 \times 10^3)</td>
<td>(5.35 \times 10^3)</td>
<td>(4.53 \times 10^3)</td>
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<tr>
<td>(M_3)</td>
<td>(-3.78 \times 10^3)</td>
<td>(-4.00 \times 10^3)</td>
<td>(-3.57 \times 10^3)</td>
<td>(-3.02 \times 10^3)</td>
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<tr>
<td>(A_0/m_{16})</td>
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<td>(\tan \beta)</td>
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<td>(m_{H^\pm})</td>
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<td>(m_{\tilde{\chi}_{1,2}^0})</td>
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<td>1140, 4235</td>
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<tr>
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<td>1.02</td>
<td>1.05</td>
<td>1.03</td>
<td>1.04</td>
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Top quark and Higgs boson masses

$0 < m_t < 220$ GeV
Top quark and Higgs boson masses

\[ 0 < m_t < 220 \text{ GeV} \]
Top quark and Higgs boson masses
SUSY SO(10) GUT

\[ \alpha_1^{-1}, \alpha_2^{-1}, \alpha_3^{-1} \]

\[ \text{MSSM} \]

\[ \log_{10}[\Lambda/\text{GeV}] \]

\[ R_{\text{HIGG}} \]

\[ m_{h} (\text{GeV}) \]

\[ m_{h} (\text{GeV}) \]

\[ y_{t}, y_{b}, y_{\tau} \]
Muchas Gracias!

Thank You!