Model Building in Grand Unified Theories

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Outline

1. Motivation
2. Overview of GUTs
3. Model Building
4. Results
5. Outlook
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Motivation

- The Standard Model: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

- Very successful, accurate predictions: $m_{H}=125.7\pm0.4$ GeV
- However, it does not explain everything:
  - ⋆ Gravity!
  - ⋆ Charge quantisation
  - ⋆ Hierarchy problem
  - ⋆ Neutrino oscillation and masses
  - ⋆ Baryon - antibaryon asymmetry
  - ⋆ Dark matter
  - ⋆ Cosmological constant

There must be an extension of the Standard Model that can explain some of these observations.

We expect to see something new during Run II of the LHC, and other experiments.
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- Symmetry \(|\mathcal{F}\rangle \leftrightarrow |\mathcal{B}\rangle\)
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- Gauge coupling unification in the MSSM (SUSY GUTs)
- Solves hierarchy problem, dark matter, ...
- Connections with superstring theory

![Graph showing the inverse of three gauge couplings as a function of log10(\(\frac{\mu}{\text{GeV}}\)).]
Motivation

Experimental motivation
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- Preliminary results: CMS $pp \rightarrow lljj$ and ATLAS $pp \rightarrow WZ$
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![Graph showing CMS and ATLAS results]

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Could be explained by a heavy gauge boson $W_R \rightarrow$ GUTs
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Cosmological motivation
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- From the Planck measurements of $A_s$

$$V^{1/4} = 2 \times 10^{16} \left( \frac{r}{0.15} \right)^{1/4}$$
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- Consistent with Planck constraints on inflation
- Scales of inflation and unification coincide
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- Motivation for hybrid inflation models with

\[ M_{inf} = 2 \times 10^{16} \text{ GeV} \]
Motivation

Current status of GUTs and SUSY

- A lot of models: SU(5), Pati-Salam, Left-right symmetry, SO(10), ...
- There is a tendency towards minimal simple models
- Next generation of experiments may exclude them
- Limits on SUSY masses \(\gtrsim 1 \text{ TeV}\)
- Not work as solution to hierarchy problem (fine tuning)

Move forward

- Need to extend to non-minimal GUT models
- Non-minimal SUSY models: "split", "compressed" SUSY, ...
- Allow for SUSY to appear at any scale

Generalised SUSY GUT model building
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Use group theory structure: Lie groups, representations, roots, weights, etc
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- Use group theory structure: Lie groups, representations, roots, weights, etc
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- Impose constraints on models:

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  - Theoretical: anomalies, gauge coupling unification, ...

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- Use group theory structure: Lie groups, representations, roots, weights, etc
- Inputs = \{group, chain, representations\}
- Impose constraints on models:
  - Theoretical: anomalies, gauge coupling unification,...
  - Phenomenological: proton decay, SUSY searches,...
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4. Results

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Overview of GUTs

Overview of GUTs


- Supergroup of the SM group

$$SU(5) \supset SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$
Overview of GUTs

\( SU(5) \) [H. Georgi and S. Glashow, Phys.Rev.Lett.32 (1974)]

- Supergroup of the SM group

\[
SU(5) \supset SU(3)_c \otimes SU(2)_L \otimes U(1)_Y
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- SM matter field content

\[
10 \equiv \begin{pmatrix}
0 & u_3^c & -u_2^c & u_1 & d_1 \\
-u_3^c & 0 & u_1^c & u_2 & 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}, \quad \bar{5} \equiv \begin{pmatrix}
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- The EW Higgs field \( 5_H = \begin{pmatrix} T_u \\ H_u \end{pmatrix} \)

\[
\bar{5}_H = \begin{pmatrix} T_d \\ H_d \end{pmatrix}
\]
Overview of GUTs

Advantages of $SU(5)$
Overview of GUTs

Advantages of SU(5)

- Predicts SM charges

\[
\begin{align*}
\frac{Q(\nu)}{Q(e^c)} &= 0, \\
\frac{Q(e)}{Q(e^c)} &= -1, \\
\frac{Q(u)}{Q(e^c)} &= \frac{2}{3}, \\
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\end{align*}$$

- It is anomaly free

$$\begin{align*}
A(\bar{5}) &= A(\bar{3}) = -A(3) \\
A(10) &= 2A(3) + A(\bar{3}) = A(3)
\end{align*}$$

$$\sum A = 0$$
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\[
\frac{Q(u)}{Q(e^c)} = \frac{2}{3}', \quad \frac{Q(d)}{Q(e^c)} = \frac{-1}{3}', \quad \frac{Q(d^c)}{Q(e^c)} = \frac{1}{3}', \quad \frac{Q(u^c)}{Q(e^c)} = \frac{-2}{3}
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- Gauge coupling unification,

\[
\alpha_3(M_{GUT}) = \alpha_2(M_{GUT}) = \alpha_1(M_{GUT})
\]
Overview of GUTs

Disadvantages of $SU(5)$

Doublet-triplet splitting

$H \sim M_{EW}$ and $T \sim M_{GUT}$

$O \left( M_{2GUT}^2 / M_{2EW}^2 \right) \sim 10^{26}$

Yukawa unification

$m_b \sim m_\tau, m_s \sim m_\mu, m_d \sim m_e$
$m_b m_\tau \sim 20\%,$
$m_s m_\mu m_d m_e \sim O(1)$

Rapid proton decay,
$\tau_{\exp} > 10^{34} y$

$\Gamma (p \rightarrow \pi^0 e^+ + \nu_e) \sim \alpha^2 m_p^5 M_X^4$, \Rightarrow $M_{GUT} \gg 10^{16} \text{GeV}$

Non-SUSY $SU(5)$ is ruled out.
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- Alternative embedding

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-u_1 & -u_2 & -u_3 & 0 & \nu^c \\
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\[1_5 \equiv (e^c)\]
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\end{pmatrix}
$$

10$_1$ ≡ $(e^c)$

- Hypercharge is a linear combination of generators $SU(5)$ and $U(1)$

$$Y = -\frac{1}{5} T_{24} + \frac{1}{5} X$$
Overview of GUTs

Differences with respect to “standard” $SU(5)$
Overview of GUTs

Differences with respect to “standard” $SU(5)$

- No full gauge coupling unification $\Rightarrow$ partial unification

\[
\begin{align*}
\alpha_2(M_{GUT}) &= \alpha_3(M_{GUT}) = \alpha_5(M_{GUT}) \\
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- SUSY version solves doublet-triple splitting, $10_1', \ 10_{-1}$

$$10_1' \ 10_1' \ 5_{-2}, \ \bar{10}_{-1} \ \bar{10}_{-1} \ \bar{5}_2$$
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- SUSY version solves doublet-triple splitting, $10', \overline{10}_{-1}$

$$10'_{1} 10'_{1} 5_{-2}, \quad \overline{10}_{-1} \overline{10}_{-1} \overline{\bar{5}}_{2}$$

- With 3 sterile neutrinos $1_{0}^{(1,2,3)}$, generates neutrino masses and mixing

$$\lambda_{j} 10_{1} \overline{10}_{-1} 1_{0}^{j}$$
Overview of GUTs

Pati-Salam $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$

Overview of GUTs

Pati-Salam $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$


- Leptons are a fourth colour

\[
\begin{pmatrix}
4, 2, 1 \\
\end{pmatrix} \equiv \begin{pmatrix}
  u_1 & u_2 & u_3 & \nu \\
  d_1 & d_2 & d_3 & e
\end{pmatrix}
\]
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- Left-handed ↔ right-handed symmetry

$$\{\bar{4}, 1, 2\} \equiv \begin{pmatrix} d_1^c & d_2^c & d_3^c & e^c \\ -u_1^c & -u_2^c & -u_3^c & -\nu^c \end{pmatrix}$$
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- And the SM Higgs is a bi-doublet $\{ 1, 2, 2 \}$
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- And the SM Higgs is a bi-doublet $\{1, 2, 2\}$

- Naturally includes right-handed $\nu$, sees-saw mechanism

\[ M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \rightarrow \begin{cases} m_\nu \sim \frac{m_D^2}{M_R} \\ m_{\nu^c} \sim M_R \end{cases} \]
Overview of GUTs

Properties of Pati-Salam

Breaking to the SM can happen in different ways. The Higgs sector depends on the breaking.

Hypercharge is a linear combination of the generators, $Y = T_3^R + \frac{1}{2}(B-L)$.

No unification of gauge couplings, $\alpha_3 = \alpha_4$, $\alpha_2 = \alpha_1 (M_{GUT})^{-1} = \frac{2}{5} \alpha_4 (M_{GUT})^{-1} + \frac{3}{5} \alpha_2 R (M_{GUT})^{-1}$

No rapid proton decay.
Overview of GUTs

Properties of Pati-Salam

- Breaking to the SM can happen in different ways
Overview of GUTs

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Overview of GUTs

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Overview of GUTs

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- Can be an intermediate step from Pati-Salam
Overview of GUTs

Left-right symmetry $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$


- Can be an intermediate step from Pati-Salam
- Matter content comes from that of P-S

$$\{4, 2, 1\} \rightarrow \{3, 2, 1, \frac{1}{3}\} \oplus \{1, 2, 1, -1\},$$
$$\{\bar{4}, 1, 2\} \rightarrow \{\bar{3}, 1, 2, -\frac{1}{3}\} \oplus \{1, 1, 2, 1\}.$$
Overview of GUTs

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\]
\[
\{\bar{4}, 1, 2\} \rightarrow \{\bar{3}, 1, 2, -\frac{1}{3}\} \oplus \{1, 1, 2, 1\}.
\]

- Predicts the existence of a $W_R$, e.g. $M_{W_R} \sim 2$ TeV

[F. F. Deppisch, T. G. et al, Phys.Rev.D90, 053014 (2014)]
[F. F. Deppisch, T. G. et al, Phys.Rev.D91, 015018 (2015)]

\[
\sigma(p p \rightarrow W_R \rightarrow f N \rightarrow \tau \tau jj) [fb]
\]
\[
1.0 \quad 1.5 \quad 2.0 \quad 2.5 \quad 3.0
\]
\[
1.0 \quad 10
\]

\[
V_{eN}^2 = 0.19 \quad V_{\mu N}^2 = 0.41 \quad V_{\tau N}^2 = 1
\]
Overview of GUTs

$SO(10)$ [H. Fritzsch and P. Minkowski, Annals Phys. 93 (1975)]

The spinor representation, \( 16 \), contains all SM fermions (plus right-handed neutrino) \( 16 \equiv \{ u_1, \nu, u_2, u_3, \nu_c, u_c_1, u_c_3, u_c_2, d_1, e, d_2, d_3, e_c, d_c_1, d_c_3, d_c_2 \} \).

The EW Higgs depends on the Yukawa sector \( 16 \otimes 16 = 10 \oplus 120 \oplus 126 \).

Can predict accurate fermion masses, e.g.

\[
\begin{align*}
    m_u &= Y_{10} v_u + Y_{126} \sigma_u + Y_{120} (\omega_{10} u + \omega_{120} u), \\
    m_d &= Y_{10} v_d + Y_{126} \sigma_d + Y_{120} (\omega_{10} d + \omega_{120} d), \\
    m_e &= Y_{10} v_d - 3 Y_{126} \sigma_d + Y_{120} (\omega_{10} d - 3 \omega_{120} d), \\
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Overview of GUTs

Breakings of $SO(10)$
Overview of GUTs

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- Contains $SU(5) \otimes U(1)$ and $SU(4) \otimes SU(2) \otimes SU(2)$
Overview of GUTs

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- Most studied GUT model
Overview of GUTs

Breakings of $SO(10)$

- Contains $SU(5) \otimes U(1)$ and $SU(4) \otimes SU(2) \otimes SU(2)$

- Most studied GUT model
- We will use $SO(10)$ as the testing ground for the model building tool
Outline

1 Motivation

2 Overview of GUTs

3 Model Building

4 Results

5 Outlook
Model Building

Automatisation of model building

Main goals

- Start with a small set of inputs at the unification scale
  \{G, G\to \cdots \to G, SM, \{R\}\}
- Construct all possible models from it
  \{R\}\to \sum_i R_i
- Satisfy theoretical constraints (gauge coupling unification)
- Constrain models with phenomenological observables

Caveats

- Only Lie groups considered, no discrete symmetries
- Models are not fully determined, only group structure
- No Lagrangian or scalar potential, symmetry breaking strictly from group properties
- No exotic fermions other than gauginos and Higgsinos
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T. Gonzalo (UCL)
Model Building in GUTs
UiO, 02/09/15
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Model Building

Automatisation of model building

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Generating the models

Starting from the GUT model at $M_{\text{GUT}}$

Decompose the reps $\{R\} \rightarrow \sum_i R_i$ to the next step.

Apply constraints.

Generate all possible combinations of the representations $\{R_i\} \rightarrow 2^n$.

Repeat for next step of the chain.
Model Building

Generating the models

- Starting from the GUT model at $M_{GUT}$ scale

![](chart.png)

Group $G$, chain, $\{G \rightarrow \cdots \rightarrow F_i \rightarrow \cdots \rightarrow G_{SM}\}$ and reps $\{R\}$ at GUT scale

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Generating the models

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Diagram:

1. Group $\mathcal{G}$, chain, $\{\mathcal{G} \rightarrow \cdots \rightarrow \mathcal{F}_i \rightarrow \cdots \rightarrow \mathcal{G}_{SM}\}$ and reps $\{\mathcal{R}\}$ at GUT scale
2. Next step in the chain, $\mathcal{F}_i$
3. Next model, $\mathcal{M}_j$
4. Check constraints on $\mathcal{M}_j$
5. Generate all possible set of subreps $\{\mathcal{R}^{(i)}\}_j$
6. Add to list of submodels $\{\mathcal{SM}\}$
7. Set of models $\{\mathcal{M}\} = \{\mathcal{SM}\}$
Model Building

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Group $\mathcal{G}$, chain, $\{\mathcal{G} \rightarrow \cdots \rightarrow \mathcal{F}_i \rightarrow \cdots \rightarrow \mathcal{G}_{SM}\}$ and reps $\{\mathcal{R}\}$ at GUT scale

- Next step in the chain, $\mathcal{F}_i$
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  - fail
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Model Building

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Group $\mathcal{G}$, chain, $\{\mathcal{G} \rightarrow \cdots \mathcal{F}_i \rightarrow \cdots \mathcal{G}_{SM}\}$ and reps $\{\mathcal{R}\}$ at GUT scale
Model Building

Constraints

Chirality: different embedding of left- and right-handed fermions

Anomalies: three types
- Gauge or Adler-Bell-Jackiw anomaly
  \[ A_{abc} = \text{Tr} \left[ \{ T^a, T^b \} T^c \right] \]
- Gravitational anomaly
  \[ A = \sum_i Q_i \]
- Witten anomaly, SU(2) topology
  \[ A = n_f \mod 2 = 0 \]

Symmetry breaking: rep content includes a scalar field that decomposes into a singlet
Reproduces the SM content at \( M_{EW} \): SM fermions + a Higgs doublet (at least)
Constraints

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Model Building

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Model Building

Unification of gauge couplings

\[ \alpha_i - 1 = \alpha_{\text{GUT}} + m \sum_{j=1} \beta_{ij} \Delta t_j \]

For a set of representations calculate the slopes

\[ \beta = \frac{2}{3} \sum_f \text{S}(R_f) + \frac{1}{3} \sum_s \text{S}(R_s) - \frac{11}{3} \text{C}_2(G) \]

System of equations

\[ (\alpha - \frac{1}{3} \alpha - \frac{2}{3} \alpha - \frac{1}{3}) = (\sum R_s S(R)) - 3 \text{C}_2(G) \]

\[ B_0 \cdot \Delta t \]
Unification of gauge couplings

- Gauge RGEs are exactly solvable at one loop

\[ \alpha_i^{-1} = \alpha_{GUT}^{-1} + \sum_{j=1}^{m} b_i^j \Delta t_j \]
Model Building

Unification of gauge couplings

- Gauge RGEs are exactly solvable at one loop

\[
\alpha_i^{-1} = \alpha_{GUT}^{-1} + \sum_{j=1}^{m} b_i^j \Delta t_j
\]

- For a set of representations calculate the slopes

\[
b = \frac{2}{3} \sum_f S(\mathcal{R}_f) + \frac{1}{3} \sum_s S(\mathcal{R}_s) - \frac{11}{3} C_2(\mathcal{G}) \quad \text{(general)}
\]

\[
b = \sum_{\mathcal{R}} S(\mathcal{R}) - 3 C_2(\mathcal{G}) \quad \text{(SUSY)}
\]
Model Building

Unification of gauge couplings

- Gauge RGEs are exactly solvable at one loop

\[ \alpha_i^{-1} = \alpha_{GUT}^{-1} + \sum_{j=1}^{m} b_j^i \Delta t_j \]

- For a set of representations calculate the slopes

\[ b = \frac{2}{3} \sum_f S(\mathcal{R}_f) + \frac{1}{3} \sum_s S(\mathcal{R}_s) - \frac{11}{3} C_2(\mathcal{G}) \quad \text{(general)} \]

\[ b = \sum_{\mathcal{R}} S(\mathcal{R}) - 3 C_2(\mathcal{G}) \quad \text{(SUSY)} \]

- System of equations

\[
\begin{pmatrix}
\alpha_3^{-1} \\
\alpha_2^{-1} \\
\alpha_1^{-1}
\end{pmatrix}
= 
\begin{pmatrix}
1 & b_3^1 & b_3^2 & \cdots & b_3^m \\
1 & b_2^1 & b_2^2 & \cdots & b_2^m \\
1 & b_1^1 & b_1^2 & \cdots & b_1^m
\end{pmatrix}
\begin{pmatrix}
\alpha_{GUT} \\
\Delta t_1 \\
\Delta t_2 \\
\vdots \\
\Delta t_m
\end{pmatrix}
\equiv B_0 \cdot \Delta t
\]
We allow the SUSY breaking scale to appear in between any scale $t_k < t_{SUSY} < t_k + 1$. Above $t_{SUSY}$ we use $b_S$, the SUSY slopes; below $t_{SUSY}$ we use $b_0$ the slopes without SUSY. The matrix of slopes above change to

$$B_S = \begin{pmatrix}
(1 (b_0))_{3 1} & \cdots & (b_S)_{3 k} \\
\vdots & \ddots & \vdots \\
(1 (b_0))_{2 1} & \cdots & (b_S)_{2 k} \\
\end{pmatrix} \begin{pmatrix}
(1 (b_0))_{1 1} & \cdots & (b_S)_{1 k} \\
\vdots & \ddots & \vdots \\
(1 (b_0))_{1 1} & \cdots & (b_S)_{1 m} \\
\end{pmatrix}
$$

And the scales $\Delta t = \{ \Delta t_1, \ldots, \Delta t_k, \Delta t_{SUSY}, \Delta t_{k + 1}, \ldots, \Delta t_m \}$.
We allow the SUSY breaking scale to appear in between any scale $t_k < t_{SUSY} < t_{k+1}$.
Supersymmetry

- We allow the SUSY breaking scale to appear in between any scale $t_k < t_{SUSY} < t_{k+1}$
- Above $t_{SUSY}$ we use $b_S$, the SUSY slopes; below $t_{SUSY}$ we use $b_0$ the slopes without SUSY
Supersymmetry

- We allow the SUSY breaking scale to appear in between any scale \( t_k < t_{SUSY} < t_{k+1} \).
- Above \( t_{SUSY} \) we use \( b_S \), the SUSY slopes; below \( t_{SUSY} \) we use \( b_0 \) the slopes without SUSY.
- The matrix of slopes above change to

\[
B_S = \begin{pmatrix}
1 & (b_0)_1^3 & \cdots & (b_0)_k^3 & (b_S)_k^3 & (b_S)_{k+1}^3 & \cdots & (b_S)_m^3 \\
1 & (b_0)_1^2 & \cdots & (b_0)_k^2 & (b_S)_k^2 & (b_S)_{k+1}^2 & \cdots & (b_S)_m^2 \\
1 & (b_0)_1^1 & \cdots & (b_0)_k^1 & (b_S)_k^1 & (b_S)_{k+1}^1 & \cdots & (b_S)_m^1 \\
\end{pmatrix}
\]
Supersymmetry

- We allow the SUSY breaking scale to appear in between any scale $t_k < t_{\text{SUSY}} < t_{k+1}$
- Above $t_{\text{SUSY}}$ we use $b_s$, the SUSY slopes; below $t_{\text{SUSY}}$ we use $b_0$ the slopes without SUSY
- The matrix of slopes above change to

$$B_s = \begin{pmatrix}
1 & (b_0)^3 & \cdots & (b_0)^{3k} & (b_s)^3 & (b_s)^3_{k+1} & \cdots & (b_s)^3_{m} \\
1 & (b_0)^2 & \cdots & (b_0)^{2k} & (b_s)^2 & (b_s)^2_{k+1} & \cdots & (b_s)^2_{m} \\
1 & (b_0)^1 & \cdots & (b_0)^{1k} & (b_s)^1 & (b_s)^1_{k+1} & \cdots & (b_s)^1_{m}
\end{pmatrix}$$

- And the scales

$$\Delta t = \begin{pmatrix}
\alpha_{\text{GUT}} & \Delta t_1 & \cdots & \Delta t_k & \Delta t_{\text{SUSY}} & \Delta t_{k+1} & \cdots & \Delta t_m
\end{pmatrix}^T$$
Abelian breaking
Abelian breaking

- There are cases where there is abelian breaking

\[ U(1)_A \otimes U(1)_B \rightarrow U(1)_C \]
Abelian breaking

- There are cases where there is abelian breaking
  \[ U(1)_A \otimes U(1)_B \rightarrow U(1)_C \]
- Charge and gauge coupling
  \[ \alpha^{-1}_C = r_A^2 \alpha^{-1}_A + r_B^2 \alpha^{-1}_B, \quad Q^j_C = r_B Q^j_A - r_A Q^j_B \]
Abelian breaking

- There are cases where there is abelian breaking
  \[ U(1)_A \otimes U(1)_B \rightarrow U(1)_C \]
- Charge and gauge coupling
  \[ \alpha_C^{-1} = r_A^2 \alpha_A^{-1} + r_B^2 \alpha_B^{-1}, \quad Q^j_C = r_B Q^j_A - r_A Q^j_B \]
- The \( U(1)_Y \) coupling is calculated
  \[ \alpha_1^{-1} = \alpha_{GUT}^{-1} + r_A^2 \sum_{j=\text{mix}+1}^m b_{jA}^1 \Delta t_j + r_B^2 \sum_{j=\text{mix}+1}^m b_{jB}^1 \Delta t_j + \sum_{j=1}^{\text{mix}} b_j^C \Delta t_j, \]
Abelian breaking

- There are cases where there is abelian breaking
  \[ U(1)_A \otimes U(1)_B \rightarrow U(1)_C \]
- Charge and gauge coupling
  \[ \alpha_C^{-1} = r_A^2 \alpha_A^{-1} + r_B^2 \alpha_B^{-1}, \quad Q_C^j = r_B Q_A^j - r_A Q_B^j \]
- The \( U(1)_Y \) coupling is calculated
  \[ \alpha_1^{-1} = \alpha_{GUT}^{-1} + r_A^2 \sum_{j=\text{mix}+1}^m b_j^{1A} \Delta t_j + r_B^2 \sum_{j=\text{mix}+1}^m b_j^{1B} \Delta t_j + \sum_{j=1}^{\text{mix}} b_j^{C} \Delta t_j, \]
- The matrix of slopes changes
  \[ B_{\text{mix}} = r_A^2 B_A + r_B^2 B_B + B_C \]
Outline

1 Motivation

2 Overview of GUTs

3 Model Building

4 Results

5 Outlook
Results

Left-Right symmetric model
Results

Left-Right symmetric model

- Model at $M_{GUT}$: group, chain and reps
Results

Left-Right symmetric model

- Model at $M_{GUT}$: group, chain and reps
- Group: $SO(10)$
Results

Left-Right symmetric model

- Model at $M_{GUT}$: group, chain and reps
- Group: $SO(10)$
- Breaking chain:

\[
SO(10) \downarrow
\]

\[
SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \downarrow
\]

\[
SU(3)_C \otimes SU(2)_L \otimes U(1)_Y
\]
Results

Left-Right symmetric model

- Model at $M_{GUT}$: group, chain and reps
- Group: $SO(10)$
- Breaking chain:

\[
SO(10) \\
\downarrow \\
SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \\
\downarrow \\
SU(3)_C \otimes SU(2)_L \otimes U(1)_Y
\]

- Set of representations

\[\mathcal{R}_i = \{16^3_F, 10, 45^2, 126, \overline{126}\}\]
Results

Representations at the intermediate scale $M_{LR}$

The number of possible combinations is

$$N = 2^n$$

We constrain to have up to 5 reps at $M_{LR}$.
Results

Representations at the intermediate scale $M_{LR}$

- Decomposition of scalar reps $R_i$

\[ 10 \rightarrow \{3, 1, 1, \frac{1}{2}\} \oplus \{\bar{3}, 1, 1, -\frac{1}{2}\} \oplus \{1, 2, 2, 0\}, \]
\[ 45 \rightarrow \{3, 2, 2, \frac{1}{2}\} \oplus \{\bar{3}, 2, 2, -\frac{1}{2}\} \oplus \{8, 1, 1, 0\} \oplus \{\bar{3}, 1, 1, 1\} \oplus \{1, 3, 1, 0\} \]
\[ \oplus \{3, 1, 1, -1\} \oplus \{1, 1, 3, 0\} \oplus \{1, 1, 1, 0\}, \]
\[ 126 \rightarrow \{8, 2, 2, 0\} \oplus \{6, 3, 1, -\frac{1}{2}\} \oplus \{\bar{6}, 1, 3, \frac{1}{2}\} \oplus \{\bar{3}, 2, 2, 1\} \oplus \{3, 2, 2, -1\} \]
\[ \oplus \{3, 3, 1, \frac{1}{2}\} \oplus \{\bar{3}, 1, 3, -\frac{1}{2}\} \oplus \{1, 2, 2, 0\} \oplus \{3, 1, 1, \frac{1}{2}\} \oplus \{\bar{3}, 1, 1, -\frac{1}{2}\} \]
\[ \oplus \{1, 3, 1, \frac{3}{2}\} \oplus \{1, 1, 3, -\frac{3}{2}\}, \]
\[ \bar{126} \rightarrow \{8, 2, 2, 0\} \oplus \{\bar{6}, 3, 1, \frac{1}{2}\} \oplus \{6, 1, 3, -\frac{1}{2}\} \oplus \{3, 2, 2, -1\} \oplus \{\bar{3}, 2, 2, 1\} \]
\[ \oplus \{\bar{3}, 3, 1, -\frac{1}{2}\} \oplus \{3, 1, 3, \frac{1}{2}\} \oplus \{1, 2, 2, 0\} \oplus \{\bar{3}, 1, 1, -\frac{1}{2}\} \oplus \{3, 1, 1, \frac{1}{2}\} \]
\[ \oplus \{1, 3, 1, -\frac{3}{2}\} \oplus \{1, 1, 3, \frac{3}{2}\} \]
Results

Representations at the intermediate scale $M_{LR}$

- Decomposition of scalar reps $\mathcal{R}_i$:

\[
10 \rightarrow \{3, 1, 1, \frac{1}{2}\} \oplus \{\bar{3}, 1, 1, -\frac{1}{2}\} \oplus \{1, 2, 2, 0\},
\]
\[
45 \rightarrow \{3, 2, 2, \frac{1}{2}\} \oplus \{\bar{3}, 2, 2, -\frac{1}{2}\} \oplus \{8, 1, 1, 0\} \oplus \{\bar{3}, 1, 1, 1\} \oplus \{1, 3, 1, 0\}
\]
\[
\quad \oplus \{3, 1, 1, -1\} \oplus \{1, 1, 3, 0\} \oplus \{1, 1, 1, 0\},
\]
\[
126 \rightarrow \{8, 2, 2, 0\} \oplus \{6, 3, 1, -\frac{1}{2}\} \oplus \{\bar{6}, 1, 3, \frac{1}{2}\} \oplus \{\bar{3}, 2, 2, 1\} \oplus \{3, 2, 2, -1\}
\]
\[
\quad \oplus \{3, 3, 1, \frac{1}{2}\} \oplus \{\bar{3}, 1, 3, -\frac{1}{2}\} \oplus \{1, 2, 2, 0\} \oplus \{3, 1, 1, \frac{1}{2}\} \oplus \{\bar{3}, 1, 1, -\frac{1}{2}\}
\]
\[
\quad \oplus \{1, 3, 1, \frac{3}{2}\} \oplus \{1, 1, 3, -\frac{3}{2}\},
\]
\[
\bar{126} \rightarrow \{8, 2, 2, 0\} \oplus \{\bar{6}, 3, 1, \frac{1}{2}\} \oplus \{6, 1, 3, -\frac{1}{2}\} \oplus \{3, 2, 2, -1\} \oplus \{\bar{3}, 2, 2, 1\}
\]
\[
\quad \oplus \{\bar{3}, 3, 1, -\frac{1}{2}\} \oplus \{3, 1, 3, \frac{1}{2}\} \oplus \{1, 2, 2, 0\} \oplus \{\bar{3}, 1, 1, -\frac{1}{2}\} \oplus \{3, 1, 1, \frac{1}{2}\}
\]
\[
\quad \oplus \{1, 3, 1, -\frac{3}{2}\} \oplus \{1, 1, 3, \frac{3}{2}\}
\]

- The number of possible combinations is $N = 2^n = 10^{10}$
Results

Representations at the intermediate scale $M_{LR}$

- Decomposition of scalar reps $\mathcal{R}_i$:

\[
\begin{align*}
10 & \rightarrow \{3, 1, 1, \frac{1}{2}\} \oplus \{\bar{3}, 1, 1, -\frac{1}{2}\} \oplus \{1, 2, 2, 0\}, \\
45 & \rightarrow \{3, 2, 2, \frac{1}{2}\} \oplus \{\bar{3}, 2, 2, -\frac{1}{2}\} \oplus \{8, 1, 1, 0\} \oplus \{\bar{3}, 1, 1, 1\} \oplus \{1, 3, 1, 0\} \oplus \{3, 1, 1, -1\} \oplus \{1, 1, 3, 0\} \oplus \{1, 1, 1, 0\}, \\
126 & \rightarrow \{8, 2, 2, 0\} \oplus \{6, 3, 1, -\frac{1}{2}\} \oplus \{\bar{6}, 1, 3, \frac{1}{2}\} \oplus \{\bar{3}, 2, 2, 1\} \oplus \{3, 2, 2, -1\} \oplus \{3, 3, 1, \frac{1}{2}\} \oplus \{\bar{3}, 1, 3, -\frac{1}{2}\} \oplus \{1, 2, 2, 0\} \oplus \{3, 1, 1, \frac{1}{2}\} \oplus \{\bar{3}, 1, 1, -\frac{1}{2}\} \oplus \{1, 3, 1, \frac{3}{2}\} \oplus \{1, 1, 3, -\frac{3}{2}\}, \\
\bar{126} & \rightarrow \{8, 2, 2, 0\} \oplus \{\bar{6}, 3, 1, \frac{1}{2}\} \oplus \{6, 1, 3, -\frac{1}{2}\} \oplus \{3, 2, 2, -1\} \oplus \{\bar{3}, 2, 2, 1\} \oplus \{\bar{3}, 3, 1, -\frac{1}{2}\} \oplus \{3, 1, 3, \frac{1}{2}\} \oplus \{1, 2, 2, 0\} \oplus \{\bar{3}, 1, 1, -\frac{1}{2}\} \oplus \{3, 1, 1, \frac{1}{2}\} \oplus \{1, 3, 1, -\frac{3}{2}\} \oplus \{1, 1, 3, \frac{3}{2}\}
\end{align*}
\]

- The number of possible combinations is $N = 2^n = 10^{10}$
- We constrain to have up to 5 reps at $M_{LR}$, $N \sim 4 \times 10^5$
Results

Phenomenological Constraints

- Reduce the number of models by imposing some phenomenological constraints

---

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Results

Phenomenological Constraints

- Reduce the number of models by imposing some phenomenological constraints
- Proton decay, current Super-K and projected Hyper-K limits
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<table>
<thead>
<tr>
<th></th>
<th>$\tau_p(p \rightarrow e^+ \pi^0)$</th>
<th>$M_{SUSY}$</th>
<th>$M_{LR}$</th>
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<tbody>
<tr>
<td>Current</td>
<td>$1.29 \times 10^{34}$ y</td>
<td>1 TeV</td>
<td>1 TeV</td>
</tr>
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<td>Future</td>
<td>$1.3 \times 10^{35}$ y</td>
<td>10 TeV</td>
<td>10 TeV</td>
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Results

Example model

Representations at $M_{LR}$ and $M_{SM}$ scale:

$$
R_{M_{LR}} = \{1, 3, 1, 0\} \oplus \{1, 1, 3, 49\} \oplus \{1, 2, 2, 0\} \oplus \{1, 1, 3, -49\}$$

$$
R_{M_{SM}} = \{1, 2, 1, 2\} \oplus \{1, 2, -1, 2\}
$$

RGE running for $M_{SUSY} = 10^4$ GeV

The other scales $M_{GUT}$ and $M_{LR}$ depend on $M_{SUSY}$

We obtain the limits for the scales
Example model

- Representations at $M_{LR}$ and SM scale

$$\{\mathcal{R}\}_{LR} = \left\{\{1,3,1,0\} \oplus \{1,1,3,\frac{49}{40}\} \oplus \{1,2,2,0\} \oplus \{1,1,3,-\frac{49}{40}\}\right\}$$

$$\{\mathcal{R}\}_{SM} = \left\{\{1,2,\frac{1}{2}\} \oplus \{1,2,-\frac{1}{2}\}\right\},$$
Results

Example model

- Representations at $M_{LR}$ and SM scale

$$\{\mathcal{R}\}_{LR} = \{\{1, 3, 1, 0\} \oplus \{1, 1, 3, \frac{49}{40}\} \oplus \{1, 2, 2, 0\} \oplus \{1, 1, 3, -\frac{49}{40}\}\}$$

$$\{\mathcal{R}\}_{SM} = \{\{1, 2, \frac{1}{2}\} \oplus \{1, 2, -\frac{1}{2}\}\}$$,

- RGE running for $M_{SUSY} = 10^4$ GeV
Results

Example model

- Representations at $M_{LR}$ and SM scale

\[
\{\mathcal{R}\}_{LR} = \{\{1, 3, 1, 0\} \oplus \{1, 1, 3, \frac{49}{40}\} \oplus \{1, 2, 2, 0\} \oplus \{1, 1, 3, -\frac{49}{40}\}\}
\]
\[
\{\mathcal{R}\}_{SM} = \{\{1, 2, \frac{1}{2}\} \oplus \{1, 2, -\frac{1}{2}\}\},
\]

- RGE running for $M_{SUSY} = 10^4$ GeV

- The other scales $M_{GUT}$ and $M_{LR}$ depend on $M_{SUSY}$
Results

Example model

- Representations at $M_{LR}$ and SM scale

\[
\{R\}_{LR} = \{\{1,3,1,0\} \oplus \{1,1,3,\frac{49}{40}\} \oplus \{1,2,2,0\} \oplus \{1,1,3,-\frac{49}{40}\}\}
\]
\[
\{R\}_{SM} = \{\{1,2,\frac{1}{2}\} \oplus \{1,2,-\frac{1}{2}\}\}
\]

- RGE running for $M_{SUSY} = 10^4$ GeV

- The other scales $M_{GUT}$ and $M_{LR}$ depend on $M_{SUSY}$

- We obtain the limits for the scales

\[
M_{SUSY} \in \{1.0 \times 10^3, 3.48 \times 10^4\}
\]
\[
\cup \{2.29 \times 10^{15}, 3.27 \times 10^{15}\},
\]
\[
M_{LR} \in \{8.03 \times 10^{13}, 2.79 \times 10^{15}\}
\]
\[
\cup \{1.26 \times 10^{10}, 1.32 \times 10^{10}\},
\]
\[
M_{GUT} \in \{3.78 \times 10^{15}, 1.24 \times 10^{16}\}
\]
\[
\cup \{3.01 \times 10^{15}, 3.28 \times 10^{15}\},
\]
Results

Distribution of models
Results

Distribution of models

- Without constraints
Results

Distribution of models

- Without constraints

- Current experimental constraints
Results

Distribution of models

- Without constraints

- Current experimental constraints

- Future experimental constraints
Results

Correlation between $M_{LR}$ and $M_{SUSY}$

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<th>$M_{LR}$ (GeV)</th>
<th>$M_{SUSY}$ (GeV)</th>
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Correlation between $M_{LR}$ and $M_{SUSY}$
Results

Correlation between $M_{LR}$ and $M_{SUSY}$
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Outlook

So far ...
Outlook

So far . . .

- Automated framework for GUT model building
Outlook

So far . . .

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- Using only group theory structure we have generated a large amount of models, satisfying theory constraints and gauge coupling unification
Outlook

So far . . .

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- Tested for a sample left-right symmetric models
Outlook

So far . . .

- Automated framework for GUT model building
- Using only group theory structure we have generated a large amount of models, satisfying theory constraints and gauge coupling unification
- Tested for a sample left-right symmetric models
- We have found that SUSY can exist at any scale
Outlook

So far . . .

- Automated framework for GUT model building
- Using only group theory structure we have generated a large amount of models, satisfying theory constraints and gauge coupling unification
- Tested for a sample left-right symmetric models
- We have found that SUSY can exist at any scale
- There is a correlation between SUSY and LR scale
Outlook

Models generated with this tool can be used for other analysis
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- Phenomenological analysis: minimal SUSY $SO(10)$
  
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- Effect of $SO(10)$ $D$-terms in SUSY spectrum
- Compressed and split SUSY scenarios

Sneutrino and singlet as the inflatons

- Consistent with results of Planck and BICEP2 for inflation
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What now

Same analysis for other chains (not LR)

SO → PS → LR → SM

Extend phenomenological analysis including other observables (flavour?)

Include treatment of other symmetries, e.g. discrete symmetries

Better treatment of symmetry breaking, scalar potentials

Extend to larger groups, $E_6$, $SO(12), \ldots$

Create Lagrangians, RGEs, etc

Link with other tools, GAMBIT
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Thank you!