Model Building in Grand Unified Theories

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Universitetet i Oslo, 2 Sept 2015

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Outline

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

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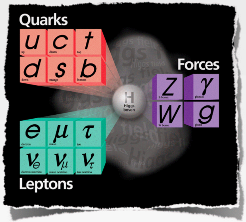
- The Standard Model: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$



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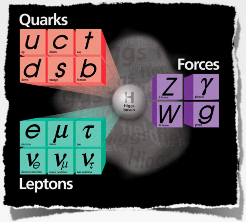

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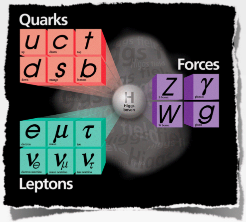

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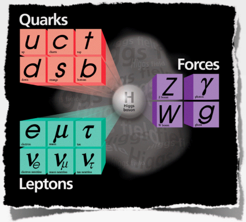

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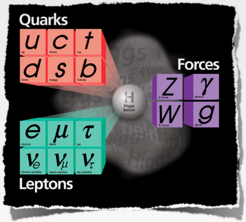

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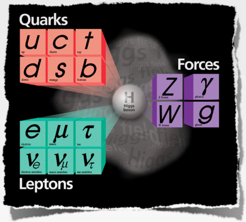

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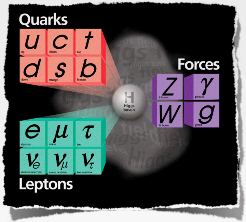

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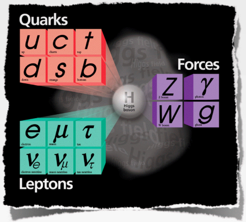

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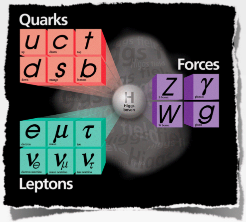

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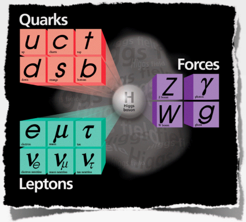

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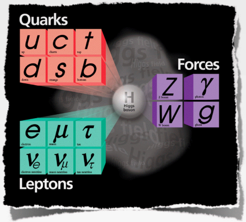

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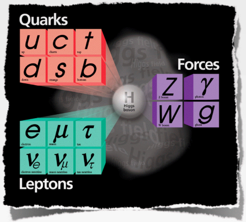

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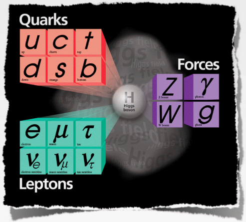

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- We expect to see something new during Run II of the LHC, and other experiments

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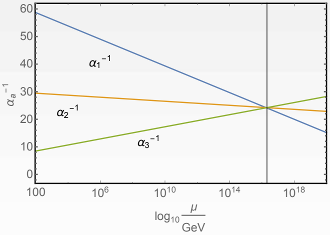

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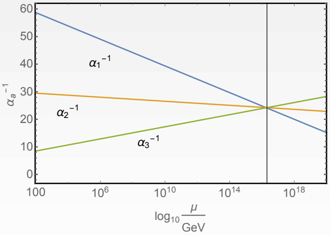

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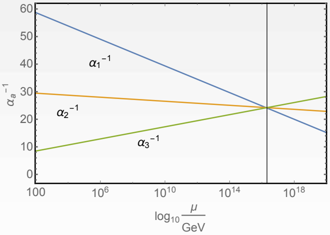

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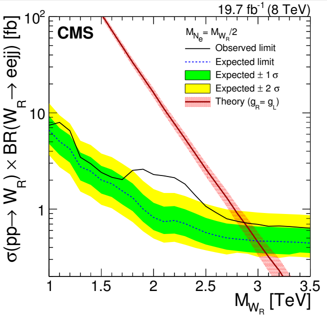

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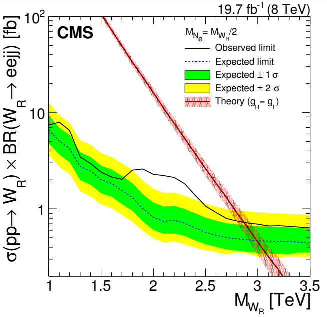

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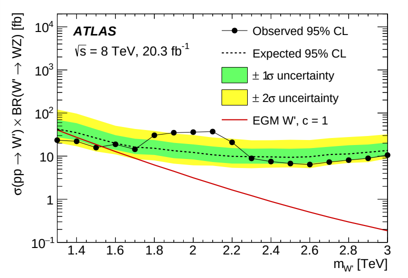

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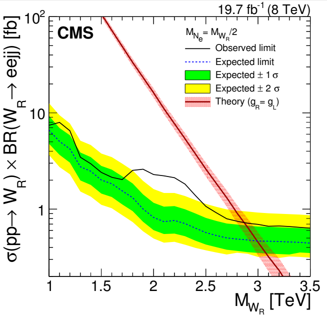

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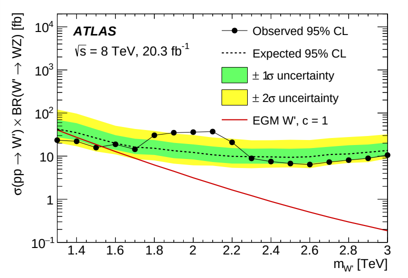

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- Could be explained by a heavy gauge boson $W_R \to$ GUTs

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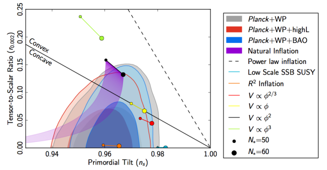

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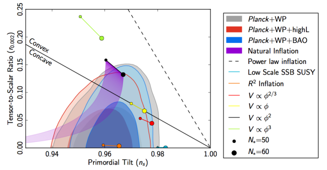

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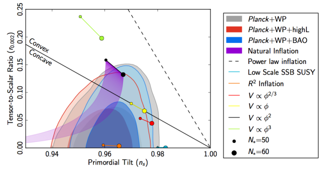

- Motivation for hybrid inflation models with

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Generalised SUSY GUT model building

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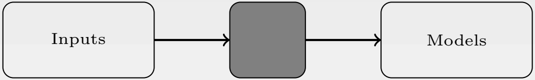

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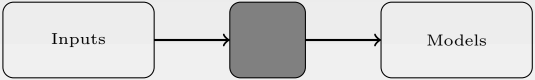

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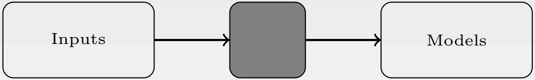

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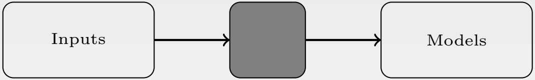

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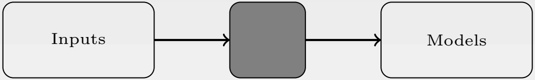

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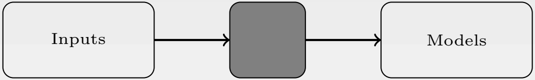

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$$\mathbf{10} \equiv \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix}, \quad \bar{\mathbf{5}} \equiv \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{pmatrix}$$

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$$\mathbf{10} \equiv \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix}, \quad \bar{\mathbf{5}} \equiv \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{pmatrix}$$

- The EW Higgs field $\mathbf{5}_H = \begin{pmatrix} T_u \\ H_u \end{pmatrix}$ $\left[\bar{\mathbf{5}}_H = \begin{pmatrix} T_d \\ H_d \end{pmatrix}\right]$

Overview of GUTs

Advantages of $SU(5)$

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- Predicts SM charges

$$\frac{Q(\nu)}{Q(e^c)} = 0, \quad \frac{Q(e)}{Q(e^c)} = -1$$

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- Gauge coupling unification,

$$\alpha_3(M_{GUT}) = \alpha_2(M_{GUT}) = \alpha_1(M_{GUT})$$

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- Doublet-triplet splitting $m_H \sim M_{EW}$ and $m_T \sim M_{GUT}$

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Non-SUSY $SU(5)$ is ruled out

Overview of GUTs

Flipped $SU(5) \otimes U(1)$

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- Alternative embedding

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- 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” $SU(5)$

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- With 3 sterile neutrinos $\mathbf{1}_0^{(1,2,3)}$, generates neutrino masses and mixing

$$\lambda_j \mathbf{10}_1\overline{\mathbf{10}}_{-1}\mathbf{1}_0^j$$

Overview of GUTs

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

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- And the SM Higgs is a bi-doublet $\{\mathbf{1},\mathbf{2},\mathbf{2}\}$
- Naturally includes right-handed ν, sees-saw mechanism

$$\mathbf{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \rightarrow \begin{cases} m_\nu \sim \frac{m_D^2}{M_R} \\ m_{\nu^c} \sim M_R \end{cases}$$

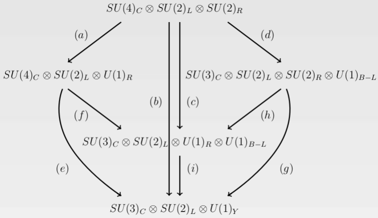
Overview of GUTs

Properties of Pati-Salam

Overview of GUTs

Properties of Pati-Salam

- Breaking to the SM can happen in different ways



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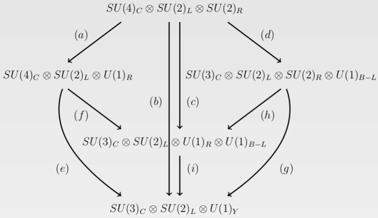

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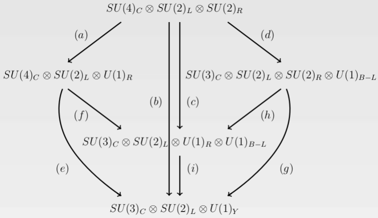

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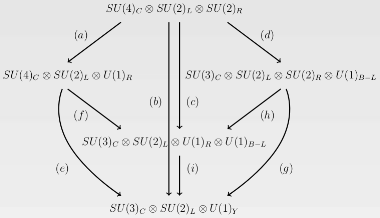

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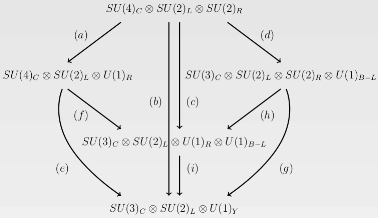

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Overview of GUTs

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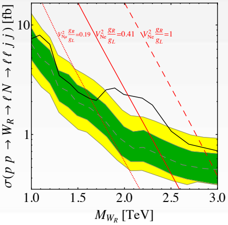
- Predicts the existence of a W_R, e.g $M_{W_R} \sim 2$ TeV

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

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



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- The spinor representation, **16** contains all SM fermions (plus right-handed neutrino)

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- Can predict accurate fermion masses, e.g.

$$\begin{aligned}
\mathbf{m}_u &= \mathbf{Y}_{10}\ v_u + \ \mathbf{Y}_{126}\ \sigma_u + \mathbf{Y}_{120}\ (\omega_u^\alpha + \ \ \omega_u^\beta), \\
\mathbf{m}_d &= \mathbf{Y}_{10}\ v_d + \ \mathbf{Y}_{126}\ \sigma_d + \mathbf{Y}_{120}\ (\omega_d^\alpha + \ \ \omega_d^\beta), \\
\mathbf{m}_e &= \mathbf{Y}_{10}\ v_d - 3\mathbf{Y}_{126}\ \sigma_d + \mathbf{Y}_{120}\ (\omega_d^\alpha - 3\ \omega_d^\beta), \\
\mathbf{m}_\nu &= \mathbf{Y}_{10}\ v_u - 3\mathbf{Y}_{126}\ \sigma_u + \mathbf{Y}_{120}\ (\omega_u^\alpha - 3\ \omega_u^\beta)
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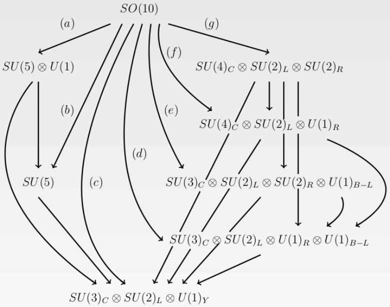

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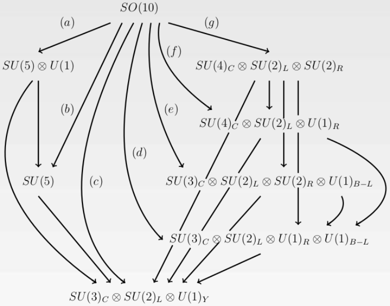

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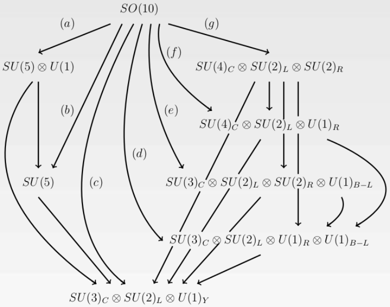

- Most studied GUT model
- We will use $SO(10)$ as the testing ground for the model building tool

Outline

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

Model Building

Automatisation of model building

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- Main goals

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$$\{\mathcal{R}\} \to \sum_i \mathcal{R}_i$$

  - ⋆ 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

Model Building

Automatisation of model building

- Main goals
  - ⋆ Start with a small set of inputs at the unification scale

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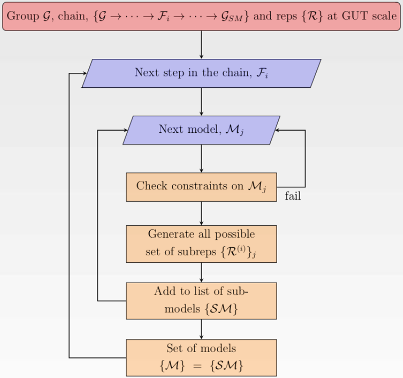
  - ⋆ No exotic fermions other than gauginos and Higgsinos

Model Building

Generating the models

Generating the models

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



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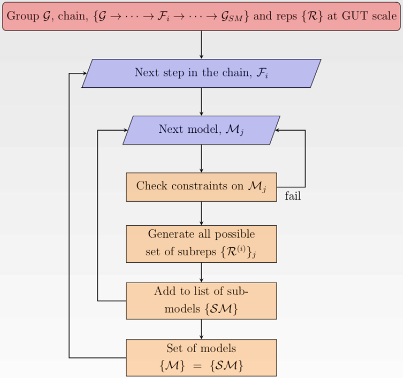

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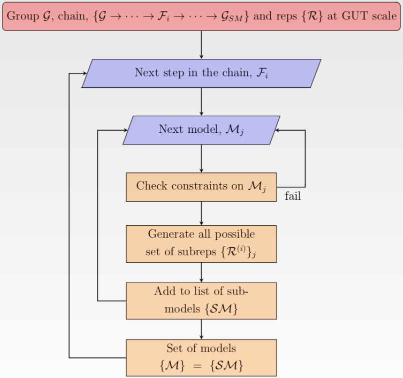

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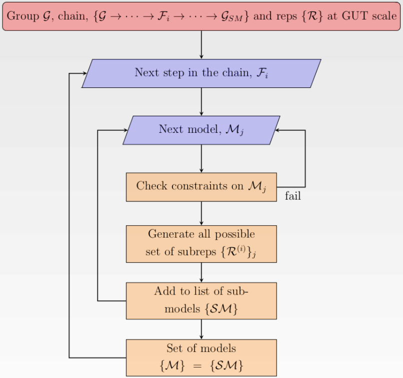

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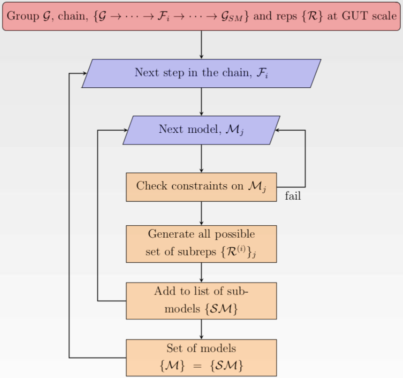

Model Building

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Model Building

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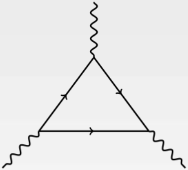

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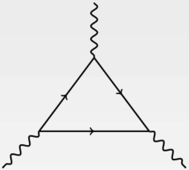

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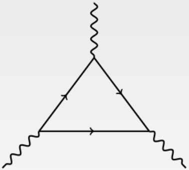

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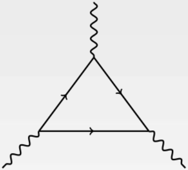

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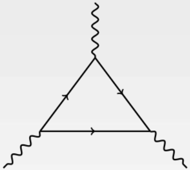

- **Symmetry breaking**: rep content includes a scalar field that decomposes into a singlet
- Reproduces the **SM content** at M_{EW}: SM fermions + a Higgs doublet (at least)

Model Building

Unification of gauge couplings

Model Building

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- Gauge RGEs are exactly solvable at one loop

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- For a set of representations calculate the slopes

$$b = \tfrac{2}{3}\sum_f S(\mathcal{R}_f) + \tfrac{1}{3}\sum_s S(\mathcal{R}_s) - \tfrac{11}{3} C_2(\mathcal{G}) \quad \text{(general)}$$
$$b = \sum_{\mathcal{R}} S(\mathcal{R}) - 3 C_2(\mathcal{G}) \quad \text{(SUSY)}$$

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- System of equations

$$\begin{pmatrix} \alpha_3^{-1} \\ \alpha_2^{-1} \\ \alpha_1^{-1} \end{pmatrix} = \begin{pmatrix} 1 & b_1^3 & b_2^3 & \cdots & b_m^3 \\ 1 & b_1^2 & b_2^2 & \cdots & b_m^2 \\ 1 & b_1^1 & b_2^1 & \cdots & b_m^1 \end{pmatrix} \begin{pmatrix} \alpha_{GUT} \\ \Delta t_1 \\ \Delta t_2 \\ \vdots \\ \Delta t_m \end{pmatrix} \equiv B_0 \cdot \Delta t$$

Model Building

Supersymmetry

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- And the scales

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

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$$\alpha_1^{-1} = \alpha_{GUT}^{-1} + r_A^2 \sum_{j=mix+1}^{m} b_j^{1A} \Delta t_j + r_B^2 \sum_{j=mix+1}^{m} b_j^{1B} \Delta t_j + \sum_{j=1}^{mix} b_j^{C} \Delta t_j,$$

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- The matrix of slopes changes

$$B_{mix} = r_A^2 B_A + r_B^2 B_B + B_C$$

Outline

Results

Left-Right symmetric model

Results

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

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SO(10) \\
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SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \\
\downarrow \\
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\end{array}
$$

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- Set of representations

$$\mathcal{R}_i = \{\mathbf{16}_F^3, \mathbf{10}, \mathbf{45}^2, \mathbf{126}, \overline{\mathbf{126}}\}$$

Results

Representations at the intermediate scale M_{LR}

Results

Representations at the intermediate scale M_{LR}

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

$$\begin{aligned}
\mathbf{10} &\to \{\mathbf{3},\mathbf{1},\mathbf{1},\ \tfrac{1}{2}\} \oplus \{\bar{\mathbf{3}},\mathbf{1},\mathbf{1},\text{-}\tfrac{1}{2}\} \oplus \{\mathbf{1},\mathbf{2},\mathbf{2},0\},\\
\mathbf{45} &\to \{\mathbf{3},\mathbf{2},\mathbf{2},\ \tfrac{1}{2}\} \oplus \{\bar{\mathbf{3}},\mathbf{2},\mathbf{2},\text{-}\tfrac{1}{2}\} \oplus \{\mathbf{8},\mathbf{1},\mathbf{1},\ 0\} \oplus \{\bar{\mathbf{3}},\mathbf{1},\mathbf{1},\ 1\} \oplus \{\mathbf{1},\mathbf{3},\mathbf{1},0\}\\
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\end{aligned}$$

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

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Phenomenological Constraints

- Reduce the number of models by imposing some phenomenological constraints

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	$\tau_p(p \to e^+\pi^0)$	M_{SUSY}	M_{LR}
Current	1.29×10^{34} y	1 TeV	1 TeV
Future	1.3×10^{35} y	10 TeV	10 TeV

Results

Example model

Results

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- Representations at M_{LR} and SM scale

$$\{\mathcal{R}\}_{LR} = \Big\{\{\mathbf{1},\mathbf{3},\mathbf{1},\ 0\} \oplus \{\mathbf{1},\mathbf{1},\mathbf{3},\ \tfrac{49}{40}\} \oplus \{\mathbf{1},\mathbf{2},\mathbf{2},\ 0\} \oplus \{\mathbf{1},\mathbf{1},\mathbf{3},\text{-}\tfrac{49}{40}\}\Big\}$$

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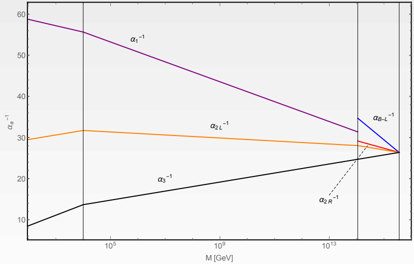
- RGE running for $M_{SUSY} = 10^4$ GeV



Results

Example model

- Representations at M_{LR} and SM scale

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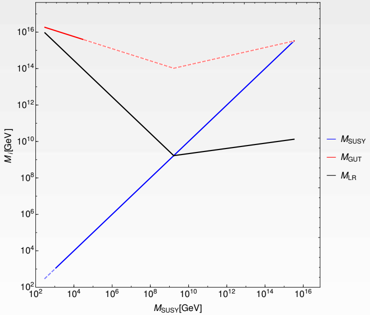

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- We obtain the limits for the scales

$$\begin{aligned} M_{SUSY} &\in \{1.0 \times 10^3, 3.48 \times 10^4\} \\ &\cup \{2.29 \times 10^{15}, 3.27 \times 10^{15}\}, \\ M_{LR} &\in \{8.03 \times 10^{13}, 2.79 \times 10^{15}\} \\ &\cup \{1.26 \times 10^{10}, 1.32 \times 10^{10}\}, \\ M_{GUT} &\in \{3.78 \times 10^{15}, 1.24 \times 10^{16}\} \\ &\cup \{3.01 \times 10^{15}, 3.28 \times 10^{15}\}, \end{aligned}$$

Results

Distribution of models

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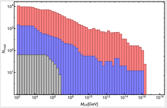
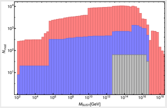
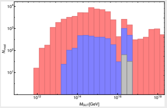
- Without constraints







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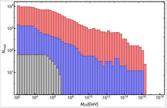
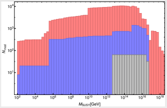
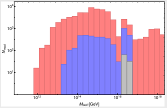

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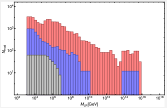
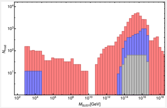
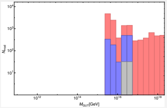

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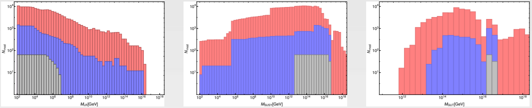

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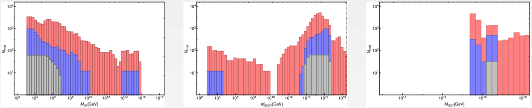
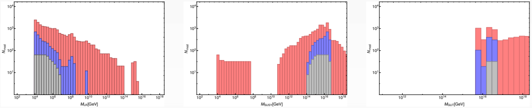


- Future experimental constraints



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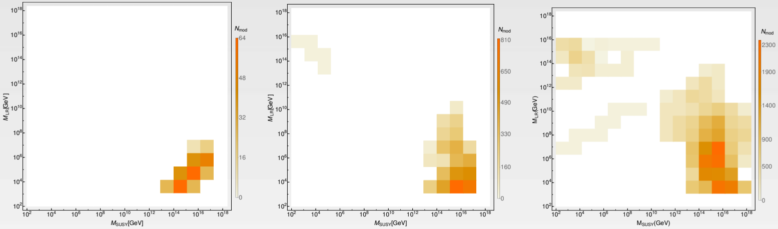

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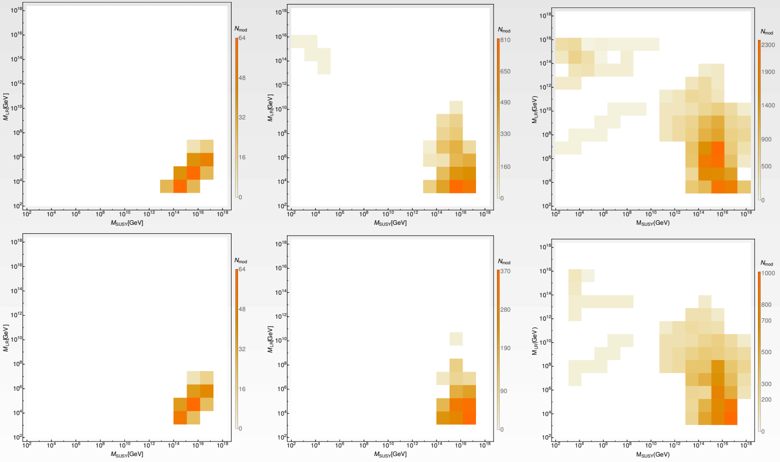

Outline

Outlook

So far . . .

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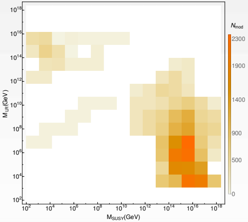
- Tested for a sample left-right symmetric models
- We have found that SUSY can exist at any scale
- There is a correlation between SUSY and LR scale



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Thank you!