The status of Supersymmetric Dark Matter after LHC Run I and alternatives from Grand Unification
1) After the results of Run I, can we still ‘guarantee’ Supersymmetry’s discovery at the LHC? Viable dark matter models in CMSSM-like tend to lie in strips (co-annihilation, funnel, focus point). How far up in energy do these strips extend?
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2) Can Non-Supersymmetric GUTs such as SO(10) provide an alternative?
Why Supersymmetry?

- Gauge Hierarchy Problem
- Gauge Coupling Unification
- Stabilization of the Electroweak Vacuum
- Radiative Electroweak Symmetry Breaking
- Dark Matter
- Improvement to low energy phenomenology?

but, $m_h \sim 125$ GeV, and no SUSY?
\[ \delta m_H^2 \simeq O(\frac{\alpha}{4\pi})(\Lambda^2 + m_B^2) - O(\frac{\alpha}{4\pi})(\Lambda^2 + m_F^2) = O(\frac{\alpha}{4\pi})(m_B^2 - m_F^2) \]

Scalar masses corrected by loops

\[ m_\phi^2 = m_o^2 + \]

Set it and Forget it!

\[ |m_B^2 - m_F^2| \lesssim 1 \text{ TeV}^2 \]
SU(5) Grand Unified Theory

\[ b_i = \begin{pmatrix} 41/10 \\ -19/6 \\ -7 \end{pmatrix} \]
Supersymmetric SU(5) Grand Unified Theory

\[ b_i = \begin{pmatrix} 33/5 \\ 1 \\ -3 \end{pmatrix} \]

is now
Standard Model Higgs potential

\[ V = \frac{\lambda}{4} \phi^4 + \frac{m^2}{2} \phi^2 \]
GUTS

Standard Model Higgs potential

\[ V = \frac{\lambda}{4} \phi^4 + \frac{m^2}{2} \phi^2 \]

Running of the Higgs quartic coupling

Figure 1: Left: SM RG evolution of the gauge couplings \( g_1 = \frac{p_5}{3} g_0, g_2 = g, g_3 = g_s \), of the top and bottom Yukawa couplings (\( y_t, y_b \)), and of the Higgs quartic coupling \( \lambda \). All couplings are defined in the \( \text{MS} \) scheme. The thickness indicates the \( \pm 1 \) uncertainty.

Right: RG evolution of varying \( M_t, M_h \) and \( \sigma \) by \( \pm 3 \). The Yukawa sector and can be considered the first complete NNLO evaluation of \( \mu \). We stress that both these two-loop terms are needed to match the sizable two-loop scale dependence of \( \lambda \) around the weak scale, caused by the \( \lambda^2 \) terms in its beta function. As a result of this improved determination of \( \mu \), we are able to obtain a significant reduction of the theoretical error on \( M_h \) compared to previous works.

Putting all the NNLO ingredients together, we estimate an overall theory error on \( M_h \) of \( \pm 1.8 \) GeV (see section 3). Our final results for the condition of absolute stability up to the Planck scale is \( M_h [\text{GeV}] > 129.4 \pm 1.4 \).●

✓

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Combining in quadrature the theoretical uncertainty with the experimental errors on \( M_t \) and \( \sigma \) we get \( M_h > 129.4 \pm 1.8 \) GeV.

From this result we conclude that vacuum stability of the SM up to the Planck scale is excluded at \( 2 \sigma \) (98% C.L. one sided) for \( M_h < 126 \) GeV.

Although the central values of Higgs and top masses do not favor a scenario with a vanishing Higgs self coupling at the Planck scale (\( M_{\text{Pl}} \))—a possibility originally proposed— these results suggest that such a scenario is unlikely.
SusyGUTS

Standard Model Higgs potential

\[ V = \frac{\lambda}{4} \phi^4 + \frac{m^2}{2} \phi^2 \]

\[ \lambda = \frac{g_1^2 + g_2^2}{2} \]

Positive definite

Stability of the vacuum ensured
Standard Model Higgs potential

\[ V = \frac{\lambda}{4} \phi^4 + \frac{m^2}{2} \phi^2 \]

\[ \lambda = \frac{g_1^2 + g_2^2}{2} \]

Positive definite

Stability of the vacuum ensured

Also for free: radiatively induced symmetry breaking
What is the MSSM

1) Add minimal number of new particles: Partners for all SM particles + 1 extra Higgs EW doublet.

2) Add minimal number of new interactions: Impose R-parity to eliminate many UNWANTED interactions.

\[ R = (-1)^{3B+L+2S} \]
CMSSM Boundary Conditions
CMSSM Boundary Conditions

- Gaugino mass Unification

\[ W = h_u H_2 Q u^c + h_d H_1 Q d^c + h_e H_1 L e^c + \mu H_2 H_1 \]

\[ \mathcal{L}_{\text{soft}} = -\frac{1}{2} M_\alpha \lambda^\alpha \lambda^\alpha - m_{ij} \phi^i \phi^j \]

\[ - A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B \mu H_2 H_1 + \text{h.c.} \]
CMSSM Boundary Conditions

- Gaugino mass Unification
- A-term Unification

\[ W = h_u H_2 Q u^c + h_d H_1 Q d^c + h_e H_1 L e^c + \mu H_2 H_1 \]

\[ \mathcal{L}_{\text{soft}} = -\frac{1}{2} M_{ij} \chi^a \chi^a - m_{ij} \phi^i \phi^{*j} \]

\[ -A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B \mu H_2 H_1 + h.c. \]
CMSSM Boundary Conditions

- Gaugino mass Unification
- A-term Unification
- Scalar mass unification

\[ W = h_u H_2 Q u^c + h_d H_1 Q d^c + h_e H_1 L e^c + \mu H_2 H_1 \]
\[ \mathcal{L}_{\text{soft}} = -\frac{1}{2} M_{ij} \bar{\chi}^i \chi^j - m^2_{ij} \phi^i \phi^j \]
- \[ -A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B \mu H_2 H_1 + \text{h.c.} \]
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- \[ -A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B \mu H_2 H_1 + \text{h.c.} \]

\[ + \tan \beta \]
CMSSM Spectra

Unification to rich spectrum + EWSB

Falk
MSSM and R-Parity

Stable DM candidate

1) Neutralinos

\[ \chi_i = \alpha_i \tilde{B} + \beta_i \tilde{W} + \gamma_i \tilde{H}_1 + \delta_i \tilde{H}_2 \]

2) Sneutrino

Excluded (unless add L-violating terms)

3) Other:

Axinos, Gravitinos, etc
The Higgs mass in the CMSSM

Ellis, Nanopoulos, Olive, Santoso
The Pre-LHC CMSSM

\( m_0 \) (GeV) \( m_{1/2} \) (GeV)

\( \tan \beta = 10 \), \( \mu > 0 \)

- \( m_h = 114 \) GeV
- \( m_{\chi^\pm} = 104 \) GeV

\( \tan \beta = 55 \), \( \mu > 0 \)

- \( m_h = 114 \) GeV

Ellis, Olive, Santoso, Spanos
Mastercode - MCMC

Multinest

- MCMC technique to sample efficiently the SUSY parameter space, and thereby construct the $\chi^2$ probability function
- Combines SoftSusy, FeynHiggs, SuperFla, SuperIso, MicrOmegas, and SSARD
- Purely frequentist approach (no priors) and relies only on the value of $\chi^2$ at the point sampled and not on the distribution of sampled points.
- 400 million points sampled

Long list of observables to constrain CMSSM parameter space

\[
\chi^2 = \sum_{i}^{N} \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} \\
+ \chi^2(M_h) + \chi^2(BR(B_s \rightarrow \mu\mu)) \\
+ \chi^2(\text{SUSY search limits}) \\
+ \sum_{i}^{M} \frac{(f_{SM_i}^{\text{obs}} - f_{SM_i}^{\text{fit}})^2}{\sigma(f_{SM_i}^{\text{SM}})^2}
\]
$\Delta \chi^2$ map of $m_0 - m_{1/2}$ plane

Mastercode 2009

Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein
Neutralino mass and Relic Density from MCMC analysis

Mastercode

Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein
Pre-Higgs Predictions

Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein
Elastic cross section from MCMC analysis
Elastic cross section from MCMC analysis
Effect of Results from LHC

~5fb⁻¹ @ 7 TeV

- jets + missing $E_T$ with/without leptons
- Heavy Higgs to $\tau\tau$
- $B$ to $\mu\mu$

~20fb⁻¹ @ 8 TeV
$m_{1/2} - m_0$ planes incl. LHC

$\tan \beta = 10$, $\mu > 0$

$\tan \beta = 55$, $\mu > 0$

$m_h = 114$ GeV

$m_{\chi^\pm} = 104$ GeV

Atlas 0l 95% CL

CMS $\alpha_T$ 95% CL

Atlas 1l 95% CL

CMS MET 95% CL

Atlas 0l 95% CL

CMS $\alpha_T$ 95% CL

Atlas 1l 95% CL

CMS MET 95% CL

Ellis, Olive, Santoso, Spanos
$m_{1/2} \sim m_0$ planes incl. LHC

$\tan \beta = 10$, $\mu > 0$

$m_h = 114$ GeV

$\tan \beta = 55$, $\mu > 0$

$m_h = 114$ GeV

Ellis, Olive, Santoso, Spanos
$m_{1/2} - m_0$ planes incl. LHC

$\tan \beta = 10$, $\mu > 0$

$m_h = 114$ GeV

LHC post EPS

$\tan \beta = 55$, $\mu > 0$

$m_h = 114$ GeV

LHC post EPS
$m_{1/2}$ - $m_0$ planes incl. LHC

$tan \beta = 10, \mu > 0$

$m_{h} = 119$ GeV

$tan \beta = 55, \mu > 0$

$m_{h} = 119$ GeV

CMSSM

Ellis, Olive, Santoso, Spanos
$m_{1/2} - m_0$ planes incl. LHC

- $\tan \beta = 10$, $\mu > 0$
  - $m_h = 114$ GeV
  - $117.5$ GeV

- $\tan \beta = 55$, $\mu > 0$
  - $m_h = 119$ GeV
$m_{1/2} - m_0$ planes incl. LHC

For $\tan \beta = 10$, $\mu > 0$, $m_h = 114$ GeV

For $\tan \beta = 55$, $\mu > 0$, $m_h = 119$ GeV

Ellis, Olive, Santoso, Spanos
$\Delta \chi^2$ map of $m_0 - m_{1/2}$ plane

CMSSM:
- Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

Low mass spectrum still observable at LHC
- 14 TeV 3000 fb$^{-1}$
- 8 TeV 20 fb$^{-1}$
Elastic scattering cross-section

CMSSM

Mastercode 2015

$\sigma^S_{SI}[\text{cm}^2]$ vs $m_{\tilde{\chi}^0_1}[\text{GeV}]$

- stau coann.
- A/H funnel
- $\tilde{\chi}_1^\pm$ coann.
- hybrid
- stop coann.
- focus point
- h funnel
- Z funnel
Elastic scattering cross-section

New LUX bound

stau coann.

A/H funnel

$\chi_1^\pm$ coann.

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h funnel

Z funnel

CMSSM

Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein
Elastic scattering cross-section

New LUX bound +PandaX
The Strips:

- Stau-coannihilation Strip
  - extends only out to ~1 TeV
- Stop-coannihilation Strip
- Funnel
  - associated with high tan β, problems with $B \rightarrow \mu\mu$
- Focus Point
Stop strip

\[ \tan \beta = 6, A_0 = -4.2 \ m_0, \mu < 0 \]

\[ m_0 \ (\text{TeV}) \]

\[ m_{1/2} \ (\text{TeV}) \]

100 TeV 3000 fb\(^{-1}\)
33 TeV 3000 fb\(^{-1}\)
14 TeV 3000 fb\(^{-1}\)
14 TeV 300 fb\(^{-1}\)
8 TeV 20 fb\(^{-1}\)

Ellis, Evans, Mustafayev, Nagata, Olive
Improved in an SU(5) superGUT extension

\[ \tan \beta = 6, A_0 = -3.5 \, m_0, \mu < 0 \]

\[ M_{\text{in}} = 10^{17} \, \text{GeV} \]
\[ \tan \beta = 5, A_0 = 0, \mu > 0 \]

100 TeV 3000 fb\(^{-1}\)
33 TeV 3000 fb\(^{-1}\)
14 TeV 3000 fb\(^{-1}\)
14 TeV 300 fb\(^{-1}\)
8 TeV 20 fb\(^{-1}\)
Direct detectability

\[ \tan\beta = 5, A_0/m_0 = 0, M_{\text{in}} = M_{\text{GUT}}, \mu > 0 \]

\[ \sigma_{SI} (\text{pb}) \]

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

\[ \tan\beta = 5, A_0/m_0 = 2.3, M_{\text{in}} = M_{\text{GUT}}, \mu > 0 \]

\[ \sigma_{SI} (\text{pb}) \]

\[ m_\chi (\text{GeV}) \]
Other Possibilities

More Constrained (fewer parameters)

- Pure Gravity Mediation
  - 2 parameter model with very large scalar masses
  - $m_0 = m_{3/2}$, $\tan \beta$
- mAMSB
  - similar to PGM, but allow $m_0 \neq m_{3/2}$
- mSUGRA
  - $B_0 = A_0 - m_0 \Rightarrow \tan \beta$ no longer free
$\tan \beta = 5, \mu > 0$

- Wino DM
- Higgsino DM

$m_{3/2}$ (GeV)

$m_0$ (GeV)

$m_{AMSB}$
Other Possibilities

Less Constrained (more parameters)

- **NUHM1,2**: $m_1^2 = m_2^2 \neq m_0^2$, $m_1^2 \neq m_2^2 \neq m_0^2$
  - $\mu$ and/or $m_A$ free
- **NUGM**
  - gluino coannihilation
- **subGUT models**: $M_{\text{in}} < M_{\text{GUT}}$
  - new parameter $M_{\text{in}}$
- **SuperGUT models**: $M_{\text{in}} > M_{\text{GUT}}$
  - requires SU(5) input couplings
NUHM1 models with $\mu$ free ($m_1 = m_2$)

Ellis, Luo, Olive, Sandick;
Ellis, Evans, Luo, Nagata, Olive, Sandick
Direct detectability

tan$\beta$=4.5, $A_0/m_0=0$, $\mu=1000$ GeV

$tan\beta=4.5$, $A_0/m_0=0$, $\mu=1050$ GeV

Ellis, Evans, Nagata, Olive, Sandick, Zheng
Why Supersymmetry (still)?

- Gauge Coupling Unification
- Gauge Hierarchy Problem
- Stabilization of the Electroweak Vacuum
- Radiative Electroweak Symmetry Breaking
- Dark Matter
- Improvement to low energy phenomenology?

but, $m_h \sim 125$ GeV, and no SUSY?
SO(10) GUT?

- Gauge Coupling Unification
- Stabilization of the Electroweak Vacuum
- Radiative Electroweak Symmetry Breaking
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Neutrino masses...
What is SO(10)

SO(10) ⊇ SU(5) × U(1)
  ⊇ SU(4) × SU(2) × SU(2)
  ⊇ others

Gauge degrees of freedom: 45

decomposition of the 45

SU(5) × U(1): \[ 45 = (24,0) + (10,4) + (10,-4) + (1,0) \]

SU(4) × SU(2) × SU(2): \[ 45 = (15,1,1) + (6,2,2) + (1,1,0) + (1,3,1) + (1,1,3) \]

(SU(4) decomposition in terms of SU(3): \[ 15 = 8 + 3 + \overline{3} + 1; \ 6 = 3 + \overline{3} \] )
What is SO(10)

SO(10) ⊃ SU(5) × U(1)
  ⊃ SU(4) × SU(2) × SU(2)
  ⊃ others

Matter degrees of freedom: fundamental 16

decomposition of the 16

SU(5) × U(1):  \(16 = (10,-1) + (\bar{5},3) + (1,-5)\)

SU(4) × SU(2) × SU(2):  \(16 = (4,1,2) + (\bar{4},2,1)\)

(SU(4) decomposition in terms of SU(3):  \(4 = 3 + 1\)

new: right-handed neutrino
What is SO(10)

\[ \text{SO}(10) \supset \text{SU}(5) \times \text{U}(1) \]
\[ \supset \text{SU}(4) \times \text{SU}(2) \times \text{SU}(2) \]
\[ \supset \text{others} \]

Higgs: see below
Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

\[
R_1 \quad \text{SO(10)} \rightarrow G_{\text{int}}
\]

<table>
<thead>
<tr>
<th>(G_{\text{int}})</th>
<th>(R_1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R)</td>
<td>210</td>
</tr>
<tr>
<td>(\text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R \otimes D)</td>
<td>54</td>
</tr>
<tr>
<td>(\text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{U}(1)_R)</td>
<td>45</td>
</tr>
<tr>
<td>(\text{SU}(3)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)<em>R \otimes \text{U}(1)</em>{B-L})</td>
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</tr>
<tr>
<td>(\text{SU}(5) \otimes \text{U}(1))</td>
<td>45, 210</td>
</tr>
<tr>
<td>Flipped SU(5) ( \otimes \text{U}(1))</td>
<td>45, 210</td>
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</table>
Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

2. Use \( \mathbf{126} \) to break \( G_{\text{int}} \) to SM

\[
\begin{align*}
\text{SO}(10) & \rightarrow G_{\text{int}} \rightarrow G_{\text{SM}} \otimes \mathbb{Z}_2 \\
R_1 & \rightarrow G_{\text{int}} \rightarrow G_{\text{SM}} \otimes \mathbb{Z}_2
\end{align*}
\]

\( R_2 = \mathbf{126} + \ldots \)

Neutrino see-saw: Majorana mass for \( \nu_R \)
from \( 16 \ 16 \ 126 \rightarrow m_{\nu_R} \sim M_{\text{int}} \) and \( m_{\nu} \sim v^2/M_{\text{int}} \)

\( \mathbb{Z}_2 \) related to matter parity and B-L

Unlike SUSY R-parity, this \( \mathbb{Z}_2 \) is not put in by hand!
Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

2. Use $126$ to break $G_{\text{int}}$ to SM

3. Pick DM representation and insure proper splitting within the multiplet, and pick low energy field content
### Remnant Z$_2$ symmetry

**Fermions from 10, 45, 54, 120, 126, or 210 representations;**

**Scalars from 16, 144**

<table>
<thead>
<tr>
<th>Model</th>
<th>$B - L$</th>
<th>SU(2)$_L$</th>
<th>$Y$</th>
<th>SO(10) representations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F^0_1$</td>
<td>1</td>
<td>0</td>
<td>45, 54, 210</td>
<td></td>
</tr>
<tr>
<td>$F^{1/2}_2$</td>
<td>2</td>
<td>1/2</td>
<td>10, 120, 126, 210'</td>
<td></td>
</tr>
<tr>
<td>$F^0_3$</td>
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<td>3</td>
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</tr>
<tr>
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Kadastik, Kannike, Raidal; Frigerio, Hambye; Mambrini, Nagata, Olive, Quevillon, Zheng; Nagata, Olive, Zheng
Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

2. Use $126$ to break $G_{\text{int}}$ to SM

3. Pick DM representation and insure proper splitting within the multiplet, and pick low energy field content

4. Use RGEs to obtain Gauge Coupling Unification
Recipe for constructing an SO(10) DM model

4. Use RGEs to obtain Gauge Coupling Unification

Fixes $M_{\text{GUT}}, M_{\text{int}}, \alpha_{\text{GUT}}$
### Examples:

#### Scalars

<table>
<thead>
<tr>
<th>Model</th>
<th>$R_{\text{DM}}$</th>
<th>$S_h^Y$</th>
<th>$\text{SO}(10)$ representation</th>
</tr>
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<td>$G_{\text{int}} = \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R(\otimes D)$</td>
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</tr>
<tr>
<td>SA$_{422}(D)$</td>
<td>4, 1, 2</td>
<td>$S_1^0$</td>
<td>16, 144</td>
</tr>
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<td>SB$_{422}(D)$</td>
<td>4, 2, 1</td>
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</tr>
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<td>4, 3, 2</td>
<td>$S_3^1$</td>
<td>144</td>
</tr>
<tr>
<td>SE$_{422}(D)$</td>
<td>4, 3, 2</td>
<td>$S_3^0$</td>
<td>144</td>
</tr>
</tbody>
</table>

| $G_{\text{int}} = \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{U}(1)_R$ |
| SA$_{421}$ | 4, 1, $-1/2$ | $S_1^0$ | 16, 144                          |
| SB$_{421}$ | 4, 2, 0       | $S_2^{1/2}$ | 16, 144                      |
| SC$_{421}$ | 4, 2, 1       | $S_2^{1/2}$ | 144                             |
| SD$_{421}$ | 4, 3, $1/2$   | $S_3^1$  | 144                             |
| SE$_{421}$ | 4, 3, $-1/2$  | $S_3^0$  | 144                             |

| $G_{\text{int}} = \text{SU}(3)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R \otimes \text{U}(1)_{B-L}(\otimes D)$ |
| SA$_{3221}(D)$ | 1, 1, 2, 1   | $S_1^0$  | 16, 144                          |
| SB$_{3221}(D)$ | 1, 2, 1, $-1$ | $S_2^{1/2}$ | 16, 144                      |
| SC$_{3221}(D)$ | 1, 2, 3, $-1$ | $S_2^{1/2}$ | 144                             |
| SD$_{3221}(D)$ | 1, 3, 2, 1   | $S_3^1$  | 144                             |
| SE$_{3221}(D)$ | 1, 3, 2, 1   | $S_3^0$  | 144                             |
Examples:

**Scalars**

Higgs portal models

Inert Higgs doublet models

<table>
<thead>
<tr>
<th>Model</th>
<th>$\log_{10} M_{\text{GUT}}$</th>
<th>$\log_{10} M_{\text{int}}$</th>
<th>$\alpha_{\text{GUT}}$</th>
<th>$\log_{10} \tau_p(p \rightarrow e^+\pi^0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{\text{int}} = \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{SA}_{422}$</td>
<td>16.33</td>
<td>11.08</td>
<td>0.0218</td>
<td>36.8 ± 1.2</td>
</tr>
<tr>
<td>$\text{SB}_{422}$</td>
<td>15.62</td>
<td>12.38</td>
<td>0.0228</td>
<td>34.0 ± 1.2</td>
</tr>
<tr>
<td>$G_{\text{int}} = \text{SU}(3)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)<em>R \otimes U(1)</em>{B-L}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{SA}_{3221}$</td>
<td>16.66</td>
<td>8.54</td>
<td>0.0217</td>
<td>38.1 ± 1.2</td>
</tr>
<tr>
<td>$\text{SB}_{3221}$</td>
<td>16.17</td>
<td>9.80</td>
<td>0.0223</td>
<td>36.2 ± 1.2</td>
</tr>
<tr>
<td>$\text{SC}_{3221}$</td>
<td>15.62</td>
<td>9.14</td>
<td>0.0230</td>
<td>34.0 ± 1.2</td>
</tr>
<tr>
<td>$G_{\text{int}} = \text{SU}(3)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)<em>R \otimes U(1)</em>{B-L} \otimes D$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{SA}_{3221D}$</td>
<td>15.58</td>
<td>10.08</td>
<td>0.0231</td>
<td>33.8 ± 1.2</td>
</tr>
<tr>
<td>$\text{SB}_{3221D}$</td>
<td>15.40</td>
<td>10.44</td>
<td>0.0233</td>
<td>33.1 ± 1.2</td>
</tr>
</tbody>
</table>

mass splitting:

\[
-\mathcal{L}_{\text{int}} = M^2 |R_{\text{DM}}|^2 + \kappa_1 R_{\text{DM}}^* R_{\text{DM}} R_1 + \{\kappa_2 R_{\text{DM}} R_{\text{DM}} R_2^* + \text{h.c.}\} \\
+ \lambda_1^1 |R_{\text{DM}}|^2 |R_1|^2 + \lambda_2^1 |R_{\text{DM}}|^2 |R_2|^2 + \{\lambda_{12}^{126} (R_{\text{DM}} R_{\text{DM}})_{126} (R_1 R_2^*)_{126} + \text{h.c.}\} \\
+ \lambda_1^{45} (R_{\text{DM}}^* R_{\text{DM}})_{45} (R_1^* R_1)_{45} + \lambda_1^{210} (R_{\text{DM}}^* R_{\text{DM}})_{210} (R_1^* R_1)_{210} \\
+ \lambda_2^{45} (R_{\text{DM}}^* R_{\text{DM}})_{45} (R_2^* R_2)_{45} + \lambda_2^{210} (R_{\text{DM}}^* R_{\text{DM}})_{210} (R_2^* R_2)_{210},
\]

other models have $M_{\text{GUT}}$ too low
Example based on scalar singlet DM \((SA_{3221})\) with
\[
G_{\text{int}} = SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L},
\]
with scalar potential
\[
V_{\text{blw}} = \mu^2 |H|^2 + \frac{1}{2} \mu_s s^2 + \frac{\lambda}{2} |H|^4 + \frac{\lambda_{sH}}{2} |H|^2 s^2 + \frac{\lambda_s}{4!} s^4.
\]
Additional fields appear at the intermediate scale.

Vacuum stability and radiative EWSB

Kadastik, Kannike, Raidal; Mambrini, Nagata, Olive, Zheng

perturbativity implies \(m_{DM} < 2 \text{ TeV}\)
Vacuum stability and radiative EWSB

Higgs mass term runs negative and depends on $\lambda_{sH}$

$\mu^2 < 0 \Leftrightarrow Q < 1 \text{ TeV}$ requires

$\lambda_{sH} > 0.4$ or $m_{DM} > 1.35 \text{ TeV}$

Kadastik, Kannike, Raidal;
Mambrini, Nagata, Olive, Zheng
Vacuum stability and radiative EWSB

Direct Detection of this candidate can be probed at XENON1T

Mambrini, Nagata, Olive, Zheng
Examples:

SM Fermion Singlets:  Produced thermally out of equilibrium  ⇔ Fermionic candidates (NETDM)

<table>
<thead>
<tr>
<th></th>
<th>Model I</th>
<th>Model II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{int}$</td>
<td>SU(4)$_C \otimes$ SU(2)$_L \otimes$ SU(2)$_R$</td>
<td>SU(4)$_C \otimes$ SU(2)$_L \otimes$ SU(2)$_R \otimes D$</td>
</tr>
<tr>
<td>$R_{DM}$</td>
<td>(1, 1, 3)$_D$ in 45$_D$</td>
<td>(15, 1, 1)$_W$ in 45$_W$</td>
</tr>
<tr>
<td>$R_1$</td>
<td>210$_R$</td>
<td>54$_R$</td>
</tr>
<tr>
<td>$R_2$</td>
<td>(10, 1, 3)$_C \oplus (1, 1, 3)$_R$</td>
<td>(10, 1, 3)$_C \oplus (10, 3, 1)$_C \oplus (15, 1, 1)$_R$</td>
</tr>
<tr>
<td>$\log_{10}(M_{int})$</td>
<td>8.08(1)</td>
<td>13.664(7)</td>
</tr>
<tr>
<td>$\log_{10}(M_{GUT})$</td>
<td>15.645(7)</td>
<td>15.87(2)</td>
</tr>
<tr>
<td>$g_{GUT}$</td>
<td>0.53055(3)</td>
<td>0.5675(2)</td>
</tr>
</tbody>
</table>

Figure 4: Running of gauge couplings. Solid (dashed) lines show the case with (without) DM and additional Higgs bosons. Blue, green, and red lines represent the running of the U(1), SU(2) and SU(3) gauge couplings, respectively.

Whether these models can give appropriate masses for light neutrinos. Next, in Sec. 5.2, we evaluate proton lifetimes in each model and discuss the testability in future proton decay experiments. Finally, we compute the abundance of DM produced by the NETDM mechanism in Sec. 5.3, and predict the reheating temperature after inflation.
Examples:

Non-Singlets: Fermions

<table>
<thead>
<tr>
<th>Model</th>
<th>$B - L$</th>
<th>$SU(2)_L$</th>
<th>$Y$</th>
<th>SO(10) representations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F^0_1$</td>
<td>1</td>
<td>0</td>
<td></td>
<td>45, 54, 210</td>
</tr>
<tr>
<td>$F^{1/2}_2$</td>
<td>2</td>
<td>1/2</td>
<td></td>
<td>10, 120, 126, 210'</td>
</tr>
<tr>
<td>$F^0_3$</td>
<td>3</td>
<td>0</td>
<td></td>
<td>45, 54, 210</td>
</tr>
<tr>
<td>$F^1_3$</td>
<td>3</td>
<td>1</td>
<td></td>
<td>54</td>
</tr>
<tr>
<td>$F^{1/2}_4$</td>
<td>4</td>
<td>1/2</td>
<td></td>
<td>210'</td>
</tr>
<tr>
<td>$F^{3/2}_4$</td>
<td>4</td>
<td>3/2</td>
<td></td>
<td>210'</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SO(10) representation</th>
<th>$SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>$(1, 3, 1)$</td>
</tr>
<tr>
<td>54</td>
<td>SM Triples (Wino)</td>
</tr>
<tr>
<td>210</td>
<td>$(15, 3, 1)$</td>
</tr>
</tbody>
</table>

<table>
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<tr>
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<th>$SU(2)_L$</th>
<th>$Y$</th>
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<td>$F^0_1$</td>
<td>1</td>
<td>0</td>
<td></td>
<td>45, 54, 210</td>
</tr>
<tr>
<td>$F^{1/2}_2$</td>
<td>2</td>
<td>1/2</td>
<td></td>
<td>10, 120, 126, 210'</td>
</tr>
<tr>
<td>$F^0_3$</td>
<td>3</td>
<td>0</td>
<td></td>
<td>45, 54, 210</td>
</tr>
<tr>
<td>$F^1_3$</td>
<td>3</td>
<td>1</td>
<td></td>
<td>54</td>
</tr>
<tr>
<td>$F^{1/2}_4$</td>
<td>4</td>
<td>1/2</td>
<td></td>
<td>210'</td>
</tr>
<tr>
<td>$F^{3/2}_4$</td>
<td>4</td>
<td>3/2</td>
<td></td>
<td>210'</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>SO(10) representation</th>
<th>$SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$</th>
<th>$B - L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10, 120, 210'</td>
<td>$(1, 2, 2)$</td>
<td>0</td>
</tr>
<tr>
<td>120, 126</td>
<td>$(15, 2, 2)$</td>
<td>0</td>
</tr>
<tr>
<td>210</td>
<td>SM Doublets (Higgsino)</td>
<td></td>
</tr>
<tr>
<td>210'</td>
<td>$(10, 2, 2) \oplus (\overline{10}, 2, 2)$</td>
<td>$\pm 2$</td>
</tr>
<tr>
<td>54, 210</td>
<td>$(1, 1, 1)$</td>
<td>0</td>
</tr>
<tr>
<td>45</td>
<td>SM Singlets for mixing (Bino)</td>
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</tr>
<tr>
<td>45, 210</td>
<td>$(1, 1, 3)$</td>
<td>0</td>
</tr>
<tr>
<td>210</td>
<td>$(15, 1, 1)$</td>
<td>0</td>
</tr>
<tr>
<td>126</td>
<td>$(10, 1, 3)$</td>
<td>2</td>
</tr>
</tbody>
</table>

Nagata, Olive, Zheng
Here again, the mass scales and proton decay lifetime are expressed in units of GeV and the intermediate scale, it turns out that gauge coupling unification is still realized, with to modify the relation, as discussed in Ref. [24].

A simple way to evade this problem is to introduce a complex (that results in large neutrino masses through the type-I seesaw mechanism since the Dirac

The mass scales and proton decay lifetime are in units of GeV and years, respectively. We find that there is only one promising model with

\[ \mathbf{R}_{\text{DM}} \]

\[ \text{Additional Higgs} \]

\[ \log_{10} M_{\text{int}} \]

\[ \log_{10} M_{\text{GUT}} \]

\[ \alpha_{\text{GUT}} \]

\[ \log_{10} \tau_p(p \rightarrow e^+ \pi^0) \]

\[ G_{\text{int}} = \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R \]

<table>
<thead>
<tr>
<th>Model</th>
<th>( R_{\text{DM}} )</th>
<th>( R'_{\text{DM}} )</th>
<th>Higgs</th>
<th>( \log_{10} M_{\text{int}} )</th>
<th>( \log_{10} M_{\text{GUT}} )</th>
<th>( \alpha_{\text{GUT}} )</th>
<th>( \log_{10} \tau_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA_{421}</td>
<td>(1, 3, 1)</td>
<td>(15, 1, 1)</td>
<td>(15, 1, 3)</td>
<td>6.54</td>
<td>17.17</td>
<td>0.0252</td>
<td>39.8 ± 1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( G_{\text{int}} = \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{U}(1)_R )</td>
<td>( (15, 1, 0)_R )</td>
<td>3.48</td>
<td>17.54</td>
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<td></td>
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<td></td>
<td>( (15, 2, 1/2)_C )</td>
<td>( G_{\text{int}} = \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R )</td>
<td>( (15, 1, 1)_R )</td>
<td>9.00</td>
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<td>( (15, 1, 3)_R )</td>
<td>( (15, 1, 1)_R )</td>
<td>5.84</td>
<td>17.01</td>
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<tr>
<td>FB_{422}</td>
<td>(1, 2, 2)_W</td>
<td>(1, 3, 1)_W</td>
<td>(15, 1, 1)_R</td>
<td>( (15, 1, 1)_R )</td>
<td>( (15, 2, 2)_C )</td>
<td>( (15, 1, 3)_R )</td>
<td></td>
</tr>
</tbody>
</table>
Summary

- LHC susy and Higgs searches have pushed CMSSM-like models to “corners” or strips
- SO(10) models contain almost all of the benefits of SUSY models:
  - gauge coupling unification, radiative EWSB, stable Higgs vacuum, stable DM candidate….
- Several possibilities in non-SUSY SO(10) models which are phenomenologically consistent with p-decay limits
- Challenge lies in detection strategies