Dark Matter after LHC Run I: Clues to 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?

2) Can we use Grand Unification to guide our SUSY searches?

3) Can Non-Supersymmetric GUTs such as SO(10) provide answers?
Grand Unification as a guide

Among the motivations for SUSY:
Gauge coupling Unification
Gauge Hierarchy Problem
Supersymmetric SU(5) Grand Unified Theory

\[
bb_i = \begin{pmatrix}
\frac{43}{10} & 19/6 \\
-3 & -3
\end{pmatrix}
\]

\[
\alpha_i - 1
\]
Grand Unification as a guide

Among the motivations for SUSY:
Gauge coupling Unification
Gauge Hierarchy Problem

Among the Consequences:
R-parity conservation (to protect proton stability)
A stable Dark Matter candidate
Grand Unification as a guide

Among the motivations for SUSY:
Gauge coupling Unification
Gauge Hierarchy Problem

Boundary conditions set at renormalization scale given by gauge coupling Unification

- Common gaugino mass: $m_{1/2}$
- Common scalar mass: $m_0 (= m_{3/2} \text{ in mSUGRA})$
- Common Trilinear mass: $A_0$
- Bilinear mass: $B_0 (= A_0 - m_0 \text{ in mSUGRA})$
Source of Supersymmetry breaking

Gravity mediation: mSUGRA/ CMSSM
\[ m_{1/2}, m_0, A_0 / \tan \beta \]

“Pure Gravity Mediation” with Anomaly mediation
\[ m_{3/2}, \tan \beta \]

Anomaly mediation: mAMSB
\[ m_{3/2}, m_0, \tan \beta \]
Other Possibilities

- NUHM1,2:
  - SO(10): $m_1^2 = m_2^2 \neq m_0^2$
  - SU(5) $m_1^2 \neq m_2^2 \neq m_0^2$
  - $\mu$ and/or $m_A$ free

- subGUT models: $M_{in} < M_{GUT}$
  - with or without mSUGRA

- superGUT models: $M_{in} > M_{GUT}$
  - with or without mSUGRA

- Relax gaugino mass universality
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

$$\chi^2 = \sum_{i}^{N} \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2}$$

$$+ \chi^2(M_h) + \chi^2(BR(B_s \rightarrow \mu \mu))$$

$$+ \chi^2(\text{SUSY search limits})$$

$$+ \sum_{i}^{M} \frac{(f_{\text{obs}}^{SM_i} - f_{\text{fit}}^{SM_i})^2}{\sigma(f_{SM_i})^2}$$

Long list of observables to constrain CMSSM parameter space

Bagnaschi, Buchmueller, Cavanaugh, Citron, Colling, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Marrouche, Nakach, Olive, Paradisi, Rogerson, Ronga, Sakurai, Martinez Santos, de Vries, Weiglein
$\Delta \chi^2$ map of $m_0 - m_{1/2}$ plane

Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein
Elastic scattering cross-section

CMSSM

$\sigma_{SI}^p$ [cm$^2$]

$10^{-40}$

$10^{-41}$

$10^{-42}$

$10^{-43}$

$10^{-44}$

$10^{-45}$

$10^{-46}$

$10^{-47}$

$10^{-48}$

$m_{\chi_1^0}$ [GeV/c$^2$]

$10^2$

$10^3$

$1-CL$

$0$

$0.1$

$0.2$

$0.3$

$0.4$

$0.5$

$0.6$

$0.7$

$0.8$

$0.9$

$1$

Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein

Mastercode 2009
$\Delta \chi^2$ map of $m_0 - m_{1/2}$ plane

CMSSM: best fit, $1\sigma$, $2\sigma$

Low mass spectrum still observable at LHC

14 TeV 3000 fb$^{-1}$
8 TeV 20 fb$^{-1}$

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

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

\[ \sigma_p^{SI} \text{[cm}^2\text{]} \]

\[ m_{\tilde{\chi}_1^0} \text{[GeV]} \]

CMSSM: best fit, 1\(\sigma\), 2\(\sigma\)

- stau coann.
- A/H funnel
- hybrid
- \(\tilde{\chi}_1^\pm\) coann.
- stop coann.
- focus point
- h funnel
- Z funnel

Ragnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein
The Strips:

- Stau-coannihilation Strip
  - extends only out to ~1 TeV
- Stop-coannihilation Strip
\[ \tan \beta = 20, A_0 = 2.3 m_0, \mu > 0 \]

\[ \tan \beta = 20, A_0 = 3.0 m_0, \mu > 0 \]

Buchmueller, Citron, Ellis, Guha, Marrouche, Olive, de Vries, Zheng

Ellis, Olive, Zheng
\[ A = 2.3m_0, \Omega \chi h^2 = 0.12, \tan \beta = 20 \]

\[ A = 3m_0, \Omega \chi h^2 = 0.12, \tan \beta = 20 \]
The Strips:

- Stau-coannihilation Strip
  - extends only out to \( \sim 1 \) TeV
- Stop-coannihilation Strip
- Funnel
  - associated with high \( \tan \beta \), problems with \( B \rightarrow \mu \mu \)
- Focus Point
Focus Point

$\tan \beta = 10, A_0 = 0, \mu > 0$

$\tan \beta = 52, A_0 = 0, \mu > 0$

Buchmueller, Citron, Ellis, Guha, Marrouche, Olive, de Vries, Zheng

Ellis, Olive, Zheng
Direct detectability into PICO [101] and the thin curves are obtained from IceCube [102] limits based on annihilations at the level. The curve is the projected LZ sensitivity and the dashed orange curve is the neutrino background.

Figure 3:

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

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

\[ \sigma_{SI} (pb) \] vs. \[ m_\chi \] (GeV)

Ellis, Evans, Nagata, Olive, Sandick, Zheng
Pure Gravity Mediation

- Two parameter model!
  - $m_0 = m_{3/2}$; tan $\beta$ (requires GM term to insure $B_0 = -m_0$)
  - gaugino masses (and A-terms) generated through loops
    $$M_1 = \frac{33}{5} \frac{g_1^2}{16\pi^2} m_{3/2},$$
    $$M_2 = \frac{g_2^2}{16\pi^2} m_{3/2},$$
    $$M_3 = -3 \frac{g_3^2}{16\pi^2} m_{3/2}.$$  

- Push towards very large masses
\[ \tan \beta = 5, \mu > 0 \]

Diagram showing the parameter space of the Minimal Supersymmetric Standard Model (mAMSB) with contours for Wino Dark Matter (DM) and Higgsino DM. The axes are labeled as:

- \( m_{3/2} \) (GeV)
- \( m_0 \) (GeV)

Key points:
- \( m_0 \approx 3 \times 10^4 \) GeV
- \( m_{3/2} \approx 1 \times 10^6 \) GeV

Mastercode 2016
NUHM1 models with μ free (m_1 = m_2)

\[ \tan \beta = 10, A_0 = 2.3 \, m_0, \mu = 500 \, \text{GeV} \]

\[ \tan \beta = 4, \quad \mu = 1050 \, \text{GeV}, A_0 = 2.3 \, m_0 \]
Relaxing GUT conditions

Figure 4. The $(m_{\tilde{q}}, m_{\tilde{g}})$ planes in the CMSSM (upper left), the NUHM1 (upper right), the NUHM2 (lower left) and the pMSSM (lower right). The red and blue solid lines are the $2 \sigma$, $3 \sigma$, and $5 \sigma$ contours, and the solid (dashed) purple lines are the current and (projected) 95% exclusion contours for $\gamma$/$E_T$ searches at the LHC (with 300 fb of data at 14 TeV). The solid lines are almost identical with the contours for 5-observation discovery with 3000 fb.

In the case of the CMSSM model we find that $m_{\tilde{t}} < 300$ GeV at the 95% CL, and we do not find a $\tilde{t}$ coannihilation region, but we do see a focus-point region and a small $\tilde{t}$ coannihilation region. The situation in the NUHM1 (upper right panel of Fig. 6) exhibits significant differences. The $\tilde{\tau}$ coannihilation region (which again dominates the 68% CL region) and the H/A funnel region still dominate the displayed portion of the $(m_{\tilde{t}}, m_{\tilde{g}})$ plane, but there is a larger hybrid region, the focus-point region has disappeared and the $\tilde{\tau}$ coannihilation region has remained small, but has moved to larger $m_{\tilde{g}}$.

We also note the appearance of a small $\tilde{t}$ coannihilation 'island' at the 95% CL in this model.

In the case of the NUHM2 (lower left panel), the 68% CL region is dominated by $\tilde{\tau}$ coannihilation, and the focus-point region has disappeared and the $\tilde{\tau}$ coannihilation region has remained small, but has moved to larger $m_{\tilde{g}}$.

The situation in the pMSSM (lower right) is similar to the NUHM1, with a significant $\tilde{\tau}$ coannihilation region and a focus-point region, but with a larger hybrid region. We also note the appearance of a small $\tilde{t}$ coannihilation 'island' at the 95% CL in this model.

de Vries, Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Marrouche, Martinez Santos, Olive, Sakurai, Weiglein
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, $m_h \sim 126$ GeV, and no SUSY?
SO(10) GUT?

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

Neutrino masses…
Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

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

<table>
<thead>
<tr>
<th>( G_{\text{int}} )</th>
<th>( R_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU(4) ( _C ) ( \otimes ) SU(2) ( _L ) ( \otimes ) SU(2) ( _R )</td>
<td>210</td>
</tr>
<tr>
<td>SU(4) ( _C ) ( \otimes ) SU(2) ( _L ) ( \otimes ) SU(2) ( _R ) ( \otimes ) D</td>
<td>54</td>
</tr>
<tr>
<td>SU(4) ( _C ) ( \otimes ) SU(2) ( _L ) ( \otimes ) U(1) ( _R )</td>
<td>45</td>
</tr>
<tr>
<td>SU(3) ( _C ) ( \otimes ) SU(2) ( _L ) ( \otimes ) SU(2) ( _R ) ( \otimes ) U(1) ( _{B-L} )</td>
<td>45</td>
</tr>
<tr>
<td>SU(3) ( _C ) ( \otimes ) SU(2) ( _L ) ( \otimes ) SU(2) ( _R ) ( \otimes ) U(1) ( _{B-L} ) ( \otimes ) D</td>
<td>210</td>
</tr>
<tr>
<td>SU(3) ( _C ) ( \otimes ) SU(2) ( _L ) ( \otimes ) U(1) ( _R ) ( \otimes ) U(1) ( _{B-L} )</td>
<td>45, 210</td>
</tr>
<tr>
<td>SU(5) ( \otimes ) U(1)</td>
<td>45, 210</td>
</tr>
<tr>
<td>Flipped SU(5) ( \otimes ) U(1)</td>
<td>45, 210</td>
</tr>
</tbody>
</table>
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

$$SO(10) \xrightarrow{R_1} G_{\text{int}} \xrightarrow{R_2} G_{\text{SM}} \otimes \mathbb{Z}_2$$

$R_2 = 126 + \ldots$

Neutrino see-saw: Majorana mass for $\nu_R$ from $16 \ 16 \ 126 \rightarrow m_{\nu_R} \sim M_{\text{int}}$
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

3. Pick DM representation and insure proper splitting within the multiplet, and pick low energy field content
### Table 2: List of SU(2) \( \leftrightarrow \) U(1) multiplets in SO(10) representations that contain an electric neutral color singlet.

<table>
<thead>
<tr>
<th>Model</th>
<th>( B - L )</th>
<th>( \text{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_{1/2} )</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^3_{1/2} )</td>
<td>3</td>
<td>1</td>
<td></td>
<td>54</td>
</tr>
<tr>
<td>( F^1_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>
<tr>
<td>( S^0_1 )</td>
<td>1</td>
<td>0</td>
<td></td>
<td>16, 144</td>
</tr>
<tr>
<td>( S^1_{1/2} )</td>
<td>2</td>
<td>1/2</td>
<td></td>
<td>16, 144</td>
</tr>
<tr>
<td>( S^0_3 )</td>
<td>3</td>
<td>0</td>
<td></td>
<td>144</td>
</tr>
<tr>
<td>( S^1_3 )</td>
<td>3</td>
<td>1</td>
<td></td>
<td>144</td>
</tr>
<tr>
<td>( \hat{F}^0_1 )</td>
<td>1</td>
<td>0</td>
<td></td>
<td>126</td>
</tr>
<tr>
<td>( \hat{F}^{1/2}_2 )</td>
<td>2</td>
<td>2</td>
<td>1/2</td>
<td>210</td>
</tr>
<tr>
<td>( \hat{F}^1_3 )</td>
<td>3</td>
<td>1</td>
<td></td>
<td>126</td>
</tr>
</tbody>
</table>
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>$\log_{10} M_{\text{GUT}}$</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>SA$_{422}$</td>
<td>16.33</td>
<td>11.08</td>
<td>0.0218</td>
<td>$36.8 \pm 1.2$</td>
</tr>
<tr>
<td>SB$_{422}$</td>
<td>15.62</td>
<td>12.38</td>
<td>0.0228</td>
<td>$34.0 \pm 1.2$</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>SA$_{3221}$</td>
<td>16.66</td>
<td>8.54</td>
<td>0.0217</td>
<td>$38.1 \pm 1.2$</td>
</tr>
<tr>
<td>SB$_{3221}$</td>
<td>16.17</td>
<td>9.80</td>
<td>0.0223</td>
<td>$36.2 \pm 1.2$</td>
</tr>
<tr>
<td>SC$_{3221}$</td>
<td>15.62</td>
<td>9.14</td>
<td>0.0230</td>
<td>$34.0 \pm 1.2$</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>SA$_{3221D}$</td>
<td>15.58</td>
<td>10.08</td>
<td>0.0231</td>
<td>$33.8 \pm 1.2$</td>
</tr>
<tr>
<td>SB$_{3221D}$</td>
<td>15.40</td>
<td>10.44</td>
<td>0.0233</td>
<td>$33.1 \pm 1.2$</td>
</tr>
</tbody>
</table>

Other models have $M_{\text{GUT}}$ too low

**Higgs portal models**

**Inert Higgs doublet models**

Nagata, Olive, Zheng
Vacuum stability and radiative EWSB

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

\[
V_{\text{blw}} = \mu^2 |H|^2 + \frac{1}{2} \mu_s s^2 + \frac{\lambda}{2} |H|^4 + \frac{\lambda_s H}{2} |H|^2 s^2 + \frac{\lambda_s}{4!} s^4
\]

Additional fields appear at the intermediate scale.

perturbatitivity implies \( m_{\text{DM}} \lesssim 2 \) TeV

Mambrini, Nagata, Olive, Zheng
Vacuum stability and radiative EWSB

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

$\mu^2 < 0$ @ $Q < 1 \text{ TeV}$ requires $\lambda_{sH} > 0.4$ or $m_{\text{DM}} > 1.35 \text{ TeV}$
Examples:

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

<table>
<thead>
<tr>
<th></th>
<th>Model I</th>
<th>Model II</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_{\text{int}} )</td>
<td>( \text{SU}(4)<em>C \otimes \text{SU}(2)</em>{\text{L}} \otimes \text{SU}(2)_{\text{R}} )</td>
<td>( \text{SU}(4)<em>C \otimes \text{SU}(2)</em>{\text{L}} \otimes \text{SU}(2)_{\text{R}} \otimes D )</td>
</tr>
<tr>
<td>( R_{\text{DM}} )</td>
<td>((1, 1, 3)<em>{D} \text{ in } 45</em>{D})</td>
<td>((15, 1, 1)<em>{W} \text{ in } 45</em>{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)<em>{C} \oplus (1, 1, 3)</em>{R})</td>
<td>((10, 1, 3)<em>{C} \oplus (10, 3, 1)</em>{C} \oplus (15, 1, 1)_{R})</td>
</tr>
<tr>
<td>( \log_{10}(M_{\text{int}}) )</td>
<td>8.08(1)</td>
<td>13.664(7)</td>
</tr>
<tr>
<td>( \log_{10}(M_{\text{GUT}}) )</td>
<td>15.645(7)</td>
<td>15.87(2)</td>
</tr>
<tr>
<td>( g_{\text{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 \( \text{U}(1) \), \( \text{SU}(2) \) and \( \text{SU}(3) \) 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.
Non-Singlets: Fermions

<table>
<thead>
<tr>
<th>$R_{DM}$</th>
<th>Additional Higgs in $R_1$</th>
<th>$\log_{10}M_{int}$</th>
<th>$\log_{10}M_{GUT}$</th>
<th>$\alpha_{GUT}$</th>
<th>$\log_{10}\tau_p(p \to e^+\pi^0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(1,3,1)$</td>
<td>6.54</td>
<td>17.17</td>
<td>0.0252</td>
<td>39.8 ± 1.2</td>
</tr>
<tr>
<td></td>
<td>$(15,1,1)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$(15,1,3)$</td>
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</table>

$G_{int} = SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$

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<tr>
<th>Model</th>
<th>$R_{DM}$</th>
<th>$R'_{DM}$</th>
<th>Higgs</th>
<th>$\log_{10}M_{int}$</th>
<th>$\log_{10}M_{GUT}$</th>
<th>$\alpha_{GUT}$</th>
<th>$\log_{10}\tau_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA$_{421}$</td>
<td>$(1,2,1/2)_D$</td>
<td>$(15,1,0)_W$</td>
<td>$(15,1,0)_R$</td>
<td>3.48</td>
<td>17.54</td>
<td>0.0320</td>
<td>40.9 ± 1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$(15,2,1/2)_C$</td>
<td></td>
<td></td>
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$G_{int} = SU(4)_C \otimes SU(2)_L \otimes U(1)_R$

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<tr>
<td>FA$_{422}$</td>
<td>$(1,2,2)_W$</td>
<td>$(1,3,1)_W$</td>
<td>$(15,1,1)_R$</td>
<td>9.00</td>
<td>15.68</td>
<td>0.0258</td>
<td>34.0 ± 1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$(15,1,3)_R$</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>FB$_{422}$</td>
<td>$(1,2,2)_W$</td>
<td>$(1,3,1)_W$</td>
<td>$(15,1,1)_R$</td>
<td>5.84</td>
<td>17.01</td>
<td>0.0587</td>
<td>38.0 ± 1.2</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>$(15,2,2)_C$</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$(15,1,3)_R$</td>
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</tr>
</tbody>
</table>
LHC susy and Higgs searches have pushed CMSSM-like models to “corners”

Though some phenomenological solutions are still viable typically along “strips” in parameter space

NUHM models with “low” μ still promising as are subGUT models; PGM/mAMSB (with wino DM or Higgsino DM)

Several possibilities in non-SUSY SO(10) models

Challenge lies in detection strategies