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

\[ b^i = \left( \begin{array}{c} 3/5 \\ -19/6 \\ -3 \end{array} \right) \]
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: $m_0 (= m_{3/2}$ in mSUGRA)
- Common Trilinear mass: $A_0$
- Bilinear mass: $B_0 (= A_0 - m_0$ 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:** $M_{\text{in}} < M_{\text{GUT}}$
  - with or without mSUGRA
- **superGUT models:** $M_{\text{in}} > M_{\text{GUT}}$
  - with or without mSUGRA
- Relax gaugino mass universality
Long list of observables to constrain CMSSM parameter space

\[
\chi^2 = \sum_{i}^{N} \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \chi^2(M_H) + \chi^2(BR(B_s \rightarrow \mu\mu)) + \chi^2(\text{SUSY search limits}) \]

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

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

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
Δχ² map of m₀ - m₁/² plane

Mastercode 2009

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

Mastercode 2009

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

\[ \sigma_{SI}^{p} \left[ \text{cm}^2 \right] \]

\[ m_{\chi_{1}^{0}} \left[ \text{GeV/c}^2 \right] \]

\[ 10^{-40}, 10^{-41}, 10^{-42}, 10^{-43}, 10^{-44}, 10^{-45}, 10^{-46}, 10^{-47}, 10^{-48} \]

\[ 10^2, 10^3 \]
$\Delta \chi^2$ 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$^{-1}$

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

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

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

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

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

Bagnaschi, 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
Stop strip

\[ A = 2.3m_0, \Omega_{\chi}h^2 = 0.12, \tan\beta = 20 \]

\[ A = 3m_0, \Omega_{\chi}h^2 = 0.12, \tan\beta = 20 \]

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

Ellis, Olive, Zheng
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

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

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

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

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

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

\[ m_\chi \text{(GeV)} \]
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
  
  \[
  M_1 = \frac{33}{5} \frac{g_1^2}{16\pi^2} m_{3/2},
  \]
  
  \[
  M_2 = \frac{g_2^2}{16\pi^2} m_{3/2},
  \]
  
  \[
  M_3 = -3 \frac{g_3^2}{16\pi^2} m_{3/2}.
  \]
- \( \Rightarrow \) Push towards very large masses
Higgsino DM

Wino DM

$\tan \beta = 2.0$

full universality

Evans, Ibe, Olive, Yanagida
$m_{0}$ (GeV) vs. $m_{3/2}$ (GeV)

- Wino DM
- Higgsino DM

$\tan \beta = 5$, $\mu > 0$

$m_{AMSB}$

Mastercode 2016
NUHM1 models with $\mu$ free ($m_1 = m_2$)

$\tan \beta = 10, A_0 = 2.3 m_0, \mu = 500$ GeV

$\tan \beta = 4, \mu = 1050$ 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 \(2\sigma\) and 5.99\% contours, and the solid (dashed) purple lines are the current and (projected) 95\% exclusion contours for \(\cancel{E}_T\) searches at the LHC (with 300/fb of data at 14 TeV). The solid lines are almost identical with the contours for 5\text{-}\text{discovery with 3000/fb.}

model we find that \(m_\tilde{t}_1 = 300\text{ GeV at the 95\% CL, and we do not find a }\tilde{t}_1\text{ coannihilation region, but we do see a focus-point region and a small }\tilde{\pm}_1\text{ coannihilation region. The situation in the NUHM1 (upper right panel of Fig. 6) exhibits significant differences. The }\tilde{\tau}_1\text{ coannihilation region (which again dominates the 68\% CL region) and the }H/A\text{ funnel region still dominate the displayed portion of the }\((m_\tilde{t}_1, m_\tilde{\nu}_1)\)\text{ plane, but there is a larger hybrid region, the focus-point region has disappeared and the }\tilde{\pm}_1\text{ coannihilation region has remained small, but has moved to larger }m_\tilde{\nu}_1\text{.}

We also note the appearance of a small }\tilde{t}_1\text{ 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}_1\text{ coannihilation.}

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, $m_h \sim 126 \text{ GeV}$, 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**

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

   | \( G_{\text{int}} \)                                      | \( R_1 \) |
   |----------------------------------------------------------|-----------|
   | \( \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R \) | 210       |
   | \( \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R \otimes D \) | 54        |
   | \( \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{U}(1)_R \)          | 45        |
   | \( \text{SU}(3)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R \otimes \text{U}(1)_{B-L} \) | 45        |
   | \( \text{SU}(3)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R \otimes \text{U}(1)_{B-L} \otimes D \) | 210       |
   | \( \text{SU}(3)_C \otimes \text{SU}(2)_L \otimes \text{U}(1)_R \otimes \text{U}(1)_{B-L} \) | 45, 210   |
   | \( \text{SU}(5) \otimes \text{U}(1) \)                                    | 45, 210   |
   | Flipped SU(5) \( \otimes \text{U}(1) \)                                | 45, 210   |
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
Remnant $Z_2$ symmetry

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

| Model | $B - L$ | $\text{SU(2)}_L$ | $Y$ | SO(10) representations |
|-------|---------|------------------|-----|------------------------|
| $F^0_1$ | 1       | 0                |     | 45, 54, 210            |
| $F^{1/2}_2$ | 2    | 1/2              |     | 10, 120, 126, 210      |
| $F^0_3$ |         | 3                | 0   | 45, 54, 210            |
| $F^1_3$ |         | 3                | 1   | 54                     |
| $F^{1/2}_4$ | 4   | 1/2              |     | 210'                   |
| $F^{3/2}_4$ | 4    | 3/2              |     | 210'                   |
| $S^0_1$ |         | 1                | 0   | 16, 144                |
| $S^{1/2}_2$ | 2    | 1/2              |     | 16, 144                |
| $S^0_3$ |         | 3                | 0   | 144                    |
| $S^1_3$ |         | 3                | 1   | 144                    |
| $\hat{F}^0_1$ | 1  | 0                |     | 126                    |
| $\hat{F}^{1/2}_2$ | 2 | 2 | 1/2 | 210 |
| $\hat{F}^1_3$ | 3 | 1 |     | 126 |

Other references:

Kadastik, Kannike, Raidal; Frigerio, Hambye; Mambrini, Nagata, Olive, Quevillon, Zheng; Nagata, Olive, Zheng
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

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**

**Higgs portal models**

**Inert Higgs doublet models**

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

*other models have $M_{\text{GUT}}$ too low*

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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

$$V_{\text{blw}} = \mu^2 |H|^2 + \frac{1}{2} \mu_s^2 s^2 + \frac{\lambda}{2} |H|^4 + \frac{\lambda_{sH}}{2} |H|^2 s^2 + \frac{\lambda_s}{4!} s^4.$$ 

Additional fields appear at the intermediate scale.

perturbatitivity implies $m_{DM} \lesssim 2$ TeV

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

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

$\mu^2 < 0$ @ $Q < 1$ TeV requires $\lambda_{SH} > .4$ or $m_{DM} > 1.35$ TeV
Examples:

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

|                          | Model I                                                                 | Model II                                                                 |
|--------------------------|-------------------------------------------------------------------------|--------------------------------------------------------------------------|
| $G_{\text{int}}$         | $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$                             | $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R \otimes D$                      |
| $R_{\text{DM}}$          | $(1, 1, 3)_D$ in $45_D$                                                | $(15, 1, 1)_W$ in $45_W$                                                |
| $R_1$                    | $210_R$                                                                 | $54_R$                                                                  |
| $R_2$                    | $(10, 1, 3)_C \oplus (1, 1, 3)_R$                                      | $(10, 1, 3)_C \oplus (10, 3, 1)_C \oplus (15, 1, 1)_R$                  |
| $\log_{10}(M_{\text{int}})$ | 8.08(1)                                                              | 13.664(7)                                                              |
| $\log_{10}(M_{GUT})$     | 15.645(7)                                                              | 15.87(2)                                                               |
| $g_{GUT}$                | 0.53055(3)                                                             | 0.5675(2)                                                              |

Mambrini, Olive, Quevillon, Zaldivar

Mambrini, Nagata, Olive, Quevillon, Zheng
### Non-Singlets: Fermions

| $R_{DM}$ | Additional Higgs in $R_1$ | $\log_{10} M_{\text{int}}$ | $\log_{10} M_{\text{GUT}}$ | $\alpha_{\text{GUT}}$ | $\log_{10} \tau_p (p \rightarrow e^+ \pi^0)$ |
|----------|---------------------------|-----------------------------|-----------------------------|-----------------------|----------------------------------|
| $(1, 3, 1)$ | $(15, 1, 1)$ | 6.54 | 17.17 | 0.0252 | 39.8 ± 1.2 |
| $(15, 1, 3)$ | | | | | |

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

| Model | $R_{DM}$ | $R'_{DM}$ | Higgs | $\log_{10} M_{\text{int}}$ | $\log_{10} M_{\text{GUT}}$ | $\alpha_{\text{GUT}}$ | $\log_{10} \tau_p$ |
|-------|---------|-----------|-------|-----------------------------|-----------------------------|-----------------------|---------------------|
| $FA_{421}$ | $(1, 2, 1/2)_D$ | $(15, 1, 0)_W$ | $(15, 1, 0)_R$ | 3.48 | 17.54 | 0.0320 | 40.9 ± 1.2 |
| | | | $(15, 2, 1/2)_C$ | | | | |

$G_{\text{int}} = SU(4)_C \otimes SU(2)_L \otimes U(1)_R$

| Model | $R_{DM}$ | $R'_{DM}$ | Higgs | $\log_{10} M_{\text{int}}$ | $\log_{10} M_{\text{GUT}}$ | $\alpha_{\text{GUT}}$ | $\log_{10} \tau_p$ |
|-------|---------|-----------|-------|-----------------------------|-----------------------------|-----------------------|---------------------|
| $FA_{422}$ | $(1, 2, 2)_W$ | $(1, 3, 1)_W$ | $(15, 1, 1)_R$ | 9.00 | 15.68 | 0.0258 | 34.0 ± 1.2 |
| | | | $(15, 1, 3)_R$ | | | | |
| $FB_{422}$ | $(1, 2, 2)_W$ | $(1, 3, 1)_W$ | $(15, 1, 1)_R$ | 5.84 | 17.01 | 0.0587 | 38.0 ± 1.2 |
| | | | $(15, 2, 2)_C$ | | | | |
| | | | $(15, 1, 3)_R$ | | | | |
Summary

- 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” $\mu$ 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