Supersymmetric Dark Matter: CMSSM-like Models in the LHC era

1) With CMSSM-like models pushed to high mass scales, can we still ‘guarantee’ Supersymmetry’s discovery at the LHC. Viable dark matter models in the CMSSM tend to lie in strips (co-annihilation, funnel, focus point), how far up in energy do these strips extend?

2) How detectable is DM along these strips

3) Generalization of the CMSSM
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, $m_h \sim 125 \text{ GeV}$, and no SUSY?
Which Supersymmetric Model?

- MSSM with R-Parity (still more than 100 parameters)
SUSY Superpotential + Soft terms

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

\[ \langle H_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \quad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \]
\[ \tan \beta = \frac{v_2}{v_1} \]

R-parity conservation assumed
Which Supersymmetric Model?

- MSSM with R-Parity (still more than 100 parameters)
- Gaugino mass Unification
- A-term Unification
- Scalar mass unification

\[ W = h_u H_2 Q_u^c + h_d H_1 Q_d^c + h_e H_1 L_e^c + \mu H_2 H_1 \]

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

\[ - A_u h_u H_2 Q_u^c - A_d h_d H_1 Q_d^c - A_c h_c H_1 L_e^c - B \mu H_2 H_1 + h.c. \]
CMSSM Spectra

Unification to rich spectrum + EWSB

Falk
Which Supersymmetric Model?

- CMSSM (4+ parameters)
  Parameters: $m_{1/2}$, $m_0$, $A_0$, $\tan \beta$, $\text{sgn}(\mu)$ \{m$_{3/2}$\}

- Pure Gravity Mediation (PGM) (2+ parameters)
  Parameters: $m_{3/2}$, $\tan \beta$, $\text{sgn}(\mu)$

- mSUGRA (3+ parameters)
  Parameters: $m_{1/2}$, $m_{3/2}$, $A_0$, $\text{sgn}(\mu)$

- Anomaly mediation: mAMSB (3+ parameters)
  Parameters: $m_{3/2}$, $m_0$, $\tan \beta$, $\text{sgn}(\mu)$
Which Supersymmetric Model?

- **CMSSM (4+ parameters)**
  Parameters: $m_{1/2}$, $m_0$, $A_0$, $\tan \beta$, $\text{sgn}(\mu)$, $\{m_3/2\}$

- **subGUT-CMSSM (5+ parameters)**
  Parameters: $m_{1/2}$, $m_0$, $A_0$, $\tan \beta$, $M_{\text{in}}$, $\text{sgn}(\mu)$, $\{m_3/2\}$

- **NUHM (5,6+ parameters)**
  Parameters: $m_{1/2}$, $m_0$, $m_1$, $m_2$, $A_0$, $\tan \beta$, $\text{sgn}(\mu)$, $\{m_3/2\}$

- **SU(5) models (7+ parameters)**
  Parameters: $m_{1/2}$, $m_5$, $m_{10}$, $m_1$, $m_2$, $A_0$, $\tan \beta$, $\text{sgn}(\mu)$, $\{m_3/2\}$
\[ \tan \beta = 10 \ , \ \mu > 0 \]

\[ m_\chi^\pm = 104 \text{ GeV} \]

\[ m_h = 114 \text{ GeV} \]

\[ m_{1/2} = 10^4 \text{ GeV} \]

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

\[ m_{1/2} (\text{GeV}) \]
The Higgs mass in the CMSSM

Ellis, Nanopoulos, Olive, Santoso
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
Elastic scattering cross-section

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

Mastercode 2009

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

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

$m_h = 114$ GeV

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

$m_h = 119$ GeV

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

CMSSM: best fit, 1σ, 2σ

Low mass spectrum still observable at LHC

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

- stau coann.
- $A/H$ funnel
- $\tilde{\chi}^\pm_1$ 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
Elastic scattering cross-section

Mastercode 2015

New LUX bound + PandaX
The Strips:

- Stau-coannihilation Strip
  - extends only out to ~1 TeV
- Stop-coannihilation Strip
Stop strip

\[ \tan \beta = 6, A_0 = -4.2 \text{ m}_0, \mu < 0 \]

\[ \begin{align*}
\text{100 TeV} & \quad 3000 \text{ fb}^{-1} \\
\text{33 TeV} & \quad 3000 \text{ fb}^{-1} \\
\text{14 TeV} & \quad 3000 \text{ fb}^{-1} \\
\text{14 TeV} & \quad 300 \text{ fb}^{-1} \\
\text{8 TeV} & \quad 20 \text{ fb}^{-1}
\end{align*} \]

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

\[ \tan \beta = 6, \ m_{1/2} = 4 \text{ TeV}, \mu < 0 \]

\[ M_{\text{in}} = M_{\text{GUT}} \]

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

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

\[ M_{\text{in}} = 10^{17} \text{ GeV} \]
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

\[ \tan \beta = 5, A_0 = 0, \mu > 0 \]

Graph showing the relationship between \( m_0 \) (TeV) and \( m_{1/2} \) (TeV) with contour lines indicating different values of \( \tan \beta \). The graph includes points labeled 122, 123, 124, 125, 126, and a shaded region.
Direct detectability

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

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

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

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

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

\[ m_\chi \text{ (GeV)} \]
In the typical CMSSM case, due to the increased degeneracy of the SUSY particles. Then, consistent with the Planck constraint. Somewhat o

because

In this case, 1-loop corrections to these masses can di
Other Possibilities

- Pure Gravity Mediation (PGM) (2+ parameters)
  Parameters: $m_{3/2}$, $\tan \beta$, $\text{sgn}(\mu)$

- Anomaly mediation: mAMSB (3+ parameters)
  Parameters: $m_{3/2}$, $m_0$, $\tan \beta$, $\text{sgn}(\mu)$
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
Phenomenological Aspects

Higgs Mass

Neutralino mass

\[ m_h \ (\text{GeV}) \]

\[ \tan \beta \]

\[ m_{3/2} = 600 \text{ TeV} \]

\[ m_{3/2} = 400 \text{ TeV} \]

Evans, Ibe, Olive, Yanagida
Dark Matter: LSP is a wino

Potential problem for wino dark matter from Fermi/HESS
(Fan + Reese; Cohen, Lianti, Pierce, Slatyer)
PGM with small $\mu$
Higgsino DM

NUHM1-like model; use EWSB conditions to determine $m_1 = m_2 \neq m_{3/2}$

$\mu$, $\tan \beta$, $m_{3/2}$ free;
Somewhat more freedom with non-universal Higgs masses

Can also choose $\mu$, $\tan \beta$, $m_{3/2}$ free;

NUHM1-like model;
use EWSB conditions to determine $m_1 = m_2 \neq m_{3/2}$ and $c_H$ (GM term)
mAMSB

Similar to PGM, but allow $m_0 \neq m_{3/2}$

$m_0$, $\tan \beta$, $m_{3/2}$ free;
\[ m_{3/2} \text{ (GeV)} \]

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

\[ \tan \beta = 5, \mu > 0 \]

Wino DM

Higgsino DM

mAMSB
Bagnaschi, Borsato, Buchmueller, Cavanaugh, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Lucio, Luo, Martinez Santos, Olive, Riochards, Sakurai, Weiglein
Other Possibilities

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

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

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

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

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

$\sigma_{SI} (\text{pb})$

$m_{\chi} ($GeV$)$

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

$\sigma_{SI} (\text{pb})$

$m_{\chi} ($GeV$)$
NUHM1/NUHM2 mastercode results (2015)

Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein
NUHM1/NUHM2 mastercode results (2015)

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

- 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
- SU(5) models (7+ parameters)
  Parameters: \( m_{1/2}, m_5, m_{10}, m_1, m_2, A_0, \tan \beta, \text{sgn}(\mu) \)
  \{m_{3/2}\}
SU(5) mastercode results (2016)

\[ m_{1/2} \text{[GeV]} \]

\[ m_5 \text{[GeV]} \]

\[ m_{10} \text{[GeV]} \]

- \( \tilde{\tau} \) coann.
- \( \tilde{\tau}_1 \) coann. + \( H/A \)
- \( \tilde{\chi}_1^{\pm} \) coann.
- \( A/H \) funnel
- \( \tilde{u}_R/\tilde{c}_R \) coann.
- \( \tilde{\nu}_\tau \) coann.

Bagnaschi, Costa, Sakurai, Borsato, Buchmueller, Cavanaugh, Chobanova, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Lucio, Martinez Santos, Olive, Riochards, de Vreis, Weiglein
Summary

- SUSY Dark Matter ALIVE and well (?)
- CMSSM generally confined to strips in parameter space: stop strips below neutrino background; focus point fully detectable
- Higgsino Dark Matter quite generic in the focus point; NUHM1,2, and parts of mAMSB with m~1 TeV.
- extended models offer wider range of possibilities

Need to Discover DM!