
Comparison between accelerator and direct detection constraints in unification models:

- mSugra
- CMSSM
- NUHM

with: Ellis, Falk, Heinemeyer, Santoso, Spanos Weiglein
Unification Conditions

• Gaugino masses: $M_i = m_{1/2}$
• Scalar masses: $m_i = m_0$
• Trilinear terms: $A_i = A_0$

mSugra Conditions

• Gaugino masses: $m_{3/2} = m_0$
• Bilinear term: $B_0 = A_0 - m_0$
Boundary Conditions

- Input parameters: $\mu$, $m_0$, $m_{1/2}$, $A_0$, $B$. predict $M_Z$, $\tan \beta$, $m_A$

**CMSSM conditions**

- Instead CMSSM:
  Input parameters: $M_Z$, $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$
  predict $\mu$, $B$, $m_A$

**mSUGRA conditions**

- Then:
  Input parameters: $M_Z$, $m_0$, $m_{1/2}$, $A_0$, $B$ predict $\mu$, $m_A$, $\tan \beta$
Constraints

• Chargino mass limit

\[ M_{\chi^\pm} \geq 104 \text{ GeV} \]
Constrains \((M_2 \text{ and } \mu)/m_{1/2}\)

• Higgs mass limit

\[ M_H \geq 114 \text{ GeV} \]
Constrains \((m_A, M_2, A)/m_{1/2}\)
particularly at low \(\tan \beta\)

• \(b \to s \gamma\)

Constrains \((m_A)/m_{1/2}\) at high \(\tan \beta\) and \(\mu < 0\)

• Also sfermion mass limits from LEP and CDF

\[ m_f \geq 99 \text{ GeV (roughly)} \]
\(\chi\) is the LSP
• Chargino mass limit

\[ M_{\chi^\pm} \geq 104 \text{ GeV} \]

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• Also sfermion mass limits from LEP and CDF

\[ m_f \geq 99 \text{ GeV} \text{ (roughly)} \]

\(\chi\) is the LSP

• \((g-2)_\mu\)

\[ a^{\exp} - a^{\text{theo}} = (25.2 \pm 9.2) \times 10^{-10} \]

• \(B_s \to \mu^+ \mu^-\)

\(\text{BR} < 2.0 \times 10^{-7}\) from CDF and DØ

Important at large \(\tan \beta\) and small \(m_A\)
Indirect Sensitivities

\[ \chi^2 \equiv \sum_{n=1}^{4} \left( \frac{R^\text{exp}_n - R^\text{theo}_n}{\sigma_n} \right)^2 + \chi^2_{M_h} \]

- \( M_W \)
- \( \sin^2 \theta \)
- \( (g-2)_\mu \)
- \( \text{BR}( b \rightarrow s \gamma) \)
- \( M_h \)

\[ \chi^2(M_h) = -2 \log \left( \int_{-\infty}^{\infty} e^{-\chi^2(x)/2} \tilde{\Phi}(M_h - x) \, dx \right) \]

\( \chi^2(M_h) \) determined from LEP CLs

Ellis, Heinemeyer, Olive, Weiglein
How Much Dark Matter

WMAP 1  Spergel et al

Precise bounds on matter content
How Much Dark Matter

WMAP 1

Precise bounds on matter content

\[ \Omega_m h^2 = 0.135^{+0.008}_{-0.009} \]

\[ \Omega_b h^2 = 0.0224 \pm 0.0009 \]

\[ \Omega_{\text{cdm}} h^2 = 0.1126^{+0.0080}_{-0.0090} \]

or

\[ \Omega_{\text{cdm}} h^2 = 0.094 - 0.129 \ (2 \sigma) \]

WMAP 3

Spergel et al

\[ \Omega_{\text{cdm}} h^2 = 0.1045^{+0.0072}_{-0.0095} \]

or

\[ \Omega_{\text{cdm}} h^2 = 0.085 - 0.119 \ (2 \sigma) \]
Typical Regions

- No EWSB
- Focus point
- Funnel
- stau co-ann.
- Bulk
- stau LSP
Direct Detection

- Elastic scattering cross sections for $\chi p$

- Use only parameters which satisfy accelerator bounds and relic density

- Dominant contribution to spin-independent scattering

$$\mathcal{L} = \alpha_{3i} \bar{\chi} \chi \bar{q}_i q_i,$$

Through light squark exchange
  - Dominant for binos

Through Higgs exchange
  - Requires some Higgsino component
Uncertainties from hadronic matrix elements

The scalar cross section

$$\sigma_3 = \frac{4m_r^2}{\pi} [Z f_p + (A - Z)f_n]^2$$

where

$$\frac{f_p}{m_p} = \sum_{q=u,d,s} f_T^{(p)} \frac{\alpha_{3q}}{m_q} + \frac{2}{27} f_T^{(p)} \sum_{c,b,t} \frac{\alpha_{3q}}{m_q}$$

and

$$m_p f_T^{(p)} \equiv \langle p|m_q \bar{q}q|p \rangle \equiv m_q B_q$$

determined by

$$\sigma_{\pi N} \equiv \Sigma = \frac{1}{2} (m_u + m_d) (B_u + B_d)$$

will take:

$$\Sigma = 45 \text{ GeV or } 64 \text{ GeV}$$
mSugra models

- \( \tan \beta \) fixed by boundary conditions (\( B_0 = A_0 - m_0 \))
- "planes" determined by \( A_0 / m_0 \)
- Gravitino often the LSP (\( m_{3/2} = m_0 \))
The Very CMSSM (mSUGRA):

$A_0/m_0 = 3 -\sqrt{3}; \mu > 0$

$m_h = 114$ GeV

$\tan \beta = 15$

$m_h = 114$ GeV

$A_0/m_0 = 2; \mu > 0$

$\tan \beta = 30$
mSugra models

- \( \tan \beta \) fixed by boundary conditions \( (B_0 = A_0 - m_0) \)
- "planes" determined by \( A_0 / m_0 \)
- Gravitino often the LSP \( (m_{3/2} = m_0) \)
- No Funnels
- No Focus Point
mSugra models

- $\tan \beta$ fixed by boundary conditions ($B_0 = A_0 - m_0$)
- “planes” determined by $A_0 / m_0$
- Gravitino often the LSP ($m_{3/2} = m_0$)
- No Funnels
- No Focus Point
- Weak signal from $B_s \rightarrow \mu^+ \mu^-$
Indirect Sensitivities to 
Gravitino Dark Matter Models

$\chi^2$ determined predominantly by $(g-2)_\mu$ on the right 
and $m_h$ on the left
Sensitivity to GDM models

mSUGRA GDM, $A_0/m_0 = 0.75$, $\mu > 0$

$\Delta \chi^2 < 3.84$

$\Delta \chi^2 < 1$

best fit
Drop $m_{3/2} = m_0$:
Indirect Sensitivities to Neutralino Dark Matter

![Graph showing indirect sensitivities to neutralino dark matter with various values of $A_0/m_0$.]
Sensitivity to NDM models

VCMSSM NDM, $A_0/m_0 = 1.27$, $\mu > 0$

- $\Delta\chi^2 < 3.84$
- $\Delta\chi^2 < 1$
- best fit
Direct Detection of NDM in the mSugra models

VCMSSM, $\mu > 0$, $\Sigma = 45$ MeV

$\sigma$ (pb)

$0 \quad 200 \quad 400 \quad 600 \quad 800 \quad 1000$

$m_\chi$ (GeV)

CDMS II

VCMSSM, $\mu > 0$, $\Sigma = 64$ MeV

$\sigma$ (pb)

$0 \quad 200 \quad 400 \quad 600 \quad 800 \quad 1000$

$m_\chi$ (GeV)

CDMS II
CMSSM

- Drop $B_0 = A_0 - m_0$ : Select $\tan \beta$

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

- $\tan \beta = 10, \mu > 0$
- $\tan \beta = 50, \mu > 0$
Foliation in $\tan \beta$

$\mu > 0$

$m_0 \ (GeV)$

$m_{1/2} \ (GeV)$
Focus Point Region

As $m_0$ gets very large, RGE’s force $\mu$ to 0, allowing neutralino to become Higgsino like with an acceptable relic density.
Indirect Sensitivities to CMSSM models

CMSSM, $\mu > 0$, $m_t = 172.7$ GeV
$\tan\beta = 10$, $A_0 = 0$
$\tan\beta = 10$, $A_0 = +m_{1/2}$
$\tan\beta = 10$, $A_0 = -m_{1/2}$
$\tan\beta = 10$, $A_0 = +2 m_{1/2}$
$\tan\beta = 10$, $A_0 = -2 m_{1/2}$

CMSSM, $\mu > 0$, $m_t = 172.7$ GeV
$\tan\beta = 50$, $A_0 = 0$
$\tan\beta = 50$, $A_0 = +m_{1/2}$
$\tan\beta = 50$, $A_0 = -m_{1/2}$
$\tan\beta = 50$, $A_0 = +2 m_{1/2}$
$\tan\beta = 50$, $A_0 = -2 m_{1/2}$
Sensitivity to $M_W$ and $\sin^2 \theta_W$

- CMSSM, $\mu > 0$, $m_t = 172.7$
- $\tan \beta = 10$, $A_0 = 0$
- $\tan \beta = 10$, $A_0 = +m_{1/2}$
- $\tan \beta = 10$, $A_0 = -m_{1/2}$
- $\tan \beta = 10$, $A_0 = +2 m_{1/2}$
- $\tan \beta = 10$, $A_0 = -2 m_{1/2}$
Current and future sensitivities

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

- $\chi^2$, 90% CL
- $\chi^2$, 68% CL
- best fit

CMSSM, $\mu > 0$, $\tan\beta = 10$ (m$_h$, BR incl.)

- $\chi^2$, 90% CL
- $\chi^2$, 68% CL
- best fit
Using the Higgs mass to determine CMSSM parameters

Ellis, Nanopoulos, Olive, Santoso
$B_s \to \mu^+ \mu^-$

Ellis, Olive, Spanos
Direct Detection in the CMSSM

CMSSM, $\mu > 0$, $\Sigma = 45$ MeV

CMSSM, $\mu > 0$, $\Sigma = 64$ MeV

CDMS II
Direct Detection in regions of lowest $\chi^2$

![Graph showing direct detection in regions of lowest $\chi^2$. The graph plots $\sigma$ ( pb ) vs. $m_\chi$ ( GeV ) for two CMSSM models: CMSSM, $\tan\beta=50$, $\mu>0$ and CMSSM, $\tan\beta=10$, $\mu>0$. The CDMS II region is also shown with an upper limit of $\Sigma=64$ MeV. Confidence levels of 90% and 68% are indicated.](image_url)
• Drop unification of scalar masses
• All Higgs soft masses, $m_1$ and $m_2$, to be chosen independently of $m_0$
• Allows $\mu$ and $m_A$ to be free parameters
\[ m_0 - m_{1/2} \text{ plane} \]

**Ellis, Olive, Santoso**

\[
tan \beta = 10 \ , \ \mu = 400 \text{ GeV} , \ m_A = 700 \text{ GeV} \\
\text{m}_h = 114 \text{ GeV} \\
\]

\[
tan \beta = 10 \ , \ \mu = 700 \text{ GeV} , \ m_A = 400 \text{ GeV} \\
\text{m}_h = 114 \text{ GeV} \\
\]

The \( m_0 - m_{1/2} \) plane

+ CMSSM value
Indirect Sensitivities to NUHM Models

NUHM, $\chi^2_{min} = 2.55$
- $\Delta \chi^2 < 3.84$ (no CDM bound)
- $\Delta \chi^2 < 1$ (no CDM bound)
- $\Delta \chi^2 < 3.84$ (CDM bound)
- $\Delta \chi^2 < 1$ (CDM bound)
- best fit (CDM bound)
- CMSSM point

$\mu = 516, M_A = 559, A_0 = 600, \tan\beta = 10$

NUHM, $\chi^2_{min} = 5.99$
- $\Delta \chi^2 < 3.84$ (no CDM bound)
- $\Delta \chi^2 < 1$ (no CDM bound)
- $\Delta \chi^2 < 3.84$ (CDM bound)
- $\Delta \chi^2 < 1$ (CDM bound)
- best fit (CDM bound)
- CMSSM point

$\mu = 400, M_A = 700, A_0 = 0, \tan\beta = 50$
The $m_A - \mu$ plane

+ CMSSM value

Ellis, Olive, Santoso
best fit (CDM bound)

CMSSM point

$\mu$ [GeV]

$M_A$ [GeV]

NUHM, $\chi^2_{\text{min}} = 1.19$

$\Delta \chi^2 < 3.84$ (no CDM bound)

$\Delta \chi^2 < 1$ (no CDM bound)

$\Delta \chi^2 < 3.84$ (CDM bound)

$\Delta \chi^2 < 1$ (CDM bound)

CMSSM point

$m_{1/2} = 300, m_0 = 100, A_0 = 600, \tan \beta = 10$

$m_{1/2} = 500, m_0 = 300$

$A_0 = 0, \tan \beta = 50$
Direct Detection in the NUHM

NUHM, $\mu > 0$, $\Sigma = 45$ MeV

NUHM, $\mu > 0$, $\Sigma = 64$ MeV

CDMS II
Consequences for $B_s \rightarrow \mu^+ \mu^-$

CDMS Excluded models
Competition between Direct Detection and $B \rightarrow \mu^+ \mu^-$

$\tan \beta = 40$, $m_{1/2} = 500$, $m_0 = 300$

$\tan \beta = 50$, $m_{1/2} = 500$, $m_0 = 300$

EOSS
$\tan \beta = 40$, $m_{1/2} = 300$, $m_0 = 100$

$\tan \beta = 57$, $m_{1/2} = 300$, $m_0 = 100$
Low Energy Effective Susy Theories

- Drop Squark-Slepton Universality
- Retain GUT constraint

![Graphs showing LEEST, μ>0, Σ=45 MeV and LEEST, μ>0, Σ=64 MeV with CDMS II data points.](image-url)
Summary

• mSugra models most difficult to access experimental esp. if GDM

• Good indication from indirect sensitivities for ‘low’ energy signal for SUSY.

• Good prospect for Direct detection and $B \rightarrow \mu^+ \mu^-$ particularly in non CMSSM models (unless GDM)