Neutralino Dark Matter in the BMSSM

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JCAP 03(2010)007 NB, A. Goudelis
JHEP 08(2009)053 NB, K. Blum, M. Losada, Y. Nir
Motivation

The BMSSM

Dark Matter
- Correlated stop-slepton masses
- Light stops, heavy sleptons

Dark Matter Direct Detection

Dark Matter Indirect Detection
- $\gamma$-rays
- Positrons
- Antiprotons

Summary
**Outline**

1. **Motivation**
2. **The BMSSM**
3. **Dark Matter**
   - Correlated stop-slepton masses
   - Light stops, heavy sleptons
4. **Dark Matter Direct Detection**
5. **Dark Matter Indirect Detection**
   - $\gamma$-rays
   - Positrons
   - Antiprotons
6. **Summary**
MSSM Higgs potential

The MSSM contains 2 doublets of complex scalar fields of opposite hypercharge:

\[ H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \]
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\[
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\]

Full tree-level scalar Higgs potential:

\[
V_H = \left( |\mu|^2 \right) |H_u|^2 + \left( |\mu|^2 \right) |H_d|^2
\]

- Quadratic terms comes from $F$ terms in the superpotential

$\mu$: higgsino mass parameter
The MSSM contains 2 doublets of complex scalar fields of opposite hypercharge:

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V_H = \left( |\mu|^2 + m^2_{H_u} \right) |H_u|^2 + \left( |\mu|^2 + m^2_{H_d} \right) |H_d|^2 - \mu B (H_u H_d + \text{h.c.})
\]

- Quadratic terms comes from $F$ terms in the superpotential and SUSY-breaking terms
  - $\mu$: higgsino mass parameter
  - $m_H$ and $B$: SUSY-breaking mass parameters
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Full tree-level scalar Higgs potential:

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$$+ \frac{g_1^2 + g_2^2}{8} \left( |H_u|^2 - |H_d|^2 \right)^2 + \frac{1}{2} g_2^2 |H_d^\dagger H_u|^2$$

- Quadratic terms comes from $F$ terms in the superpotential
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- Quartic terms comes from $D$ terms → pure gauge couplings!
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- Quadratic terms come from \( F \) terms in the superpotential and SUSY-breaking terms
  - \( \mu \): higgsino mass parameter
  - \( m_H \) and \( B \): SUSY-breaking mass parameters

- Quartic terms come from \( D \) terms → pure gauge couplings!

- \( V_H \) is CP conserving (even though the full \( L \) violates CP)
The neutral components of the 2 Higgs fields develop vevs:

\[ \langle H_u \rangle = v_u = v \sin \beta \quad \langle H_d \rangle = v_d = v \cos \beta \]

EW symmetry breaking: \( SU(2)_L \times U(1)_Y \rightarrow U(1)_{EW} \)

The spectrum contains:
- \( h \) and \( H \): 2 CP even Higgs bosons
- \( A \): 1 CP odd Higgs boson
- \( H^+ \) and \( H^- \): 2 charged Higgs bosons
In terms of $M_A$ and $\tan \beta$ the tree level Higgs spectrum is

\[
m^2_h &= \frac{1}{2} \left[ m^2_Z + m^2_A - \sqrt{(m^2_A - m^2_Z)^2 + 4 m^2_A m^2_Z \sin^2 2\beta} \right] \\
m^2_H &= \frac{1}{2} \left[ m^2_Z + m^2_A + \sqrt{(m^2_A - m^2_Z)^2 + 4 m^2_A m^2_Z \sin^2 2\beta} \right] \\
m^2_{H^\pm} &= m^2_A + m^2_W
\]
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Tree level Higgs spectrum

In terms of $M_A$ and $\tan \beta$ the tree level Higgs spectrum is

\[
m_h^2 = \frac{1}{2} \left[ m_Z^2 + m_A^2 - \sqrt{(m_A^2 - m_Z^2)^2 + 4 m_A^2 m_Z^2 \sin^2 2\beta} \right]
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\[
m_{H^\pm}^2 = m_A^2 + m_W^2
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Important constraint: $m_h \leq \text{Min}(m_A, m_Z) | \cos 2\beta | \leq m_Z$
In terms of $M_A$ and $\tan \beta$ the tree level Higgs spectrum is

$$m_h^2 = \frac{1}{2} \left[ m_Z^2 + m_A^2 - \sqrt{(m_A^2 - m_Z^2)^2 + 4 m_A^2 m_Z^2 \sin^2 2\beta} \right]$$

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Important constraint: $m_h \leq \text{Min}(m_A, m_Z) |\cos 2\beta| \leq m_Z$

The LEP II bound $m_h \gtrsim 114 \, \text{GeV}$ is already violated!
In terms of $M_A$ and $\tan \beta$ the tree level Higgs spectrum is

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\begin{align*}
m_h^2 &= \frac{1}{2} \left[ m_Z^2 + m_A^2 - \sqrt{(m_A^2 - m_Z^2)^2 + 4 m_A^2 m_Z^2 \sin^2 2\beta} \right] \\
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\end{align*}
$$

Important constraint: $m_h \leq \text{Min}(m_A, m_Z) |\cos 2\beta| \leq m_Z$

The LEP II bound $m_h \gtrsim 114 \text{ GeV}$ is already violated!

$\rightarrow$ To avoid a contradiction we need both large $\tan \beta$ and large radiative corrections
Radiative corrections

Most important RC comes from loops of tops and stops:

$$
\delta_{1\text{-loop}} m_h^2 \sim \frac{12}{16\pi} \left[ \ln \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{|X_t|^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \ln \frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2} \right] \\
+ \frac{1}{2} \left( \frac{|X_t|^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \right)^2 \left( 2 - \frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \ln \frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2} \right)
$$

$$X_t \equiv A_t - \mu \cot \beta$$
Radiative corrections

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\[ \delta_{1\text{-}\text{loop}} m_h^2 \sim \frac{12}{16\pi} \left[ \ln \frac{m_{t_1} m_{t_2}}{m_t^2} + \frac{|X_t|^2}{m_{t_1}^2 - m_{t_2}^2} \ln \frac{m_{t_1}^2}{m_{t_2}^2} + \frac{1}{2} \left( \frac{|X_t|^2}{m_{t_1}^2 - m_{t_2}^2} \right)^2 \left( 2 - \frac{m_{t_1}^2 + m_{t_2}^2}{m_{t_1}^2 - m_{t_2}^2} \ln \frac{m_{t_1}^2}{m_{t_2}^2} \right) \right] \]

\[ X_t \equiv A_t - \mu \cot \beta \]

Consistency with LEP II achieved with

- **Heavy stops**  \( m_{\tilde{t}} \sim 600 \text{ GeV to few TeV} \)

- **However, the superpartners make the theory natural and they should not be too heavy**
Motivation

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Radiative corrections

Most important RC comes from loops of tops and stops:

\[
\delta_{1\text{-loop}} m_h^2 \sim \frac{12}{16\pi} \left\{ \ln \frac{m_{\tilde{t}_1}}{m_t^2} + \frac{|X_t|^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \ln \frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2} \right. \\
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\(X_t \equiv A_t - \mu \cot \beta\)

Consistency with LEP II achieved with

- **Heavy stops**  \( m_{\tilde{t}} \sim 600 \text{ GeV to few TeV} \)
- **Large stop mixing**
- **However, large** \( A_t \)-**terms are hard to achieve in specific models of SUSY breaking**
Radiative corrections

Most important RC comes from loops of tops and stops:

$$\delta_{\text{1-loop}} m_h^2 \sim \frac{12}{16\pi} \left[ \ln \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{|X_t|^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \ln \frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2} \right]$$

$$+ \frac{1}{2} \left( \frac{|X_t|^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \right)^2 \left( 2 - \frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \ln \frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2} \right)$$

$$X_t \equiv A_t - \mu \cot \beta$$

Consistency with LEP II achieved with

- **Heavy stops** \( m_{\tilde{t}} \sim 600 \text{ GeV} \) to few TeV
- **Large stop mixing**

\[ \text{x} \] SUSY Little Hierarchy Problem
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Assume that there is New Physics beyond the MSSM at a scale $M$, much above the electroweak scale $m_Z$ and the scale of the SUSY breaking terms $m_{\text{susy}}$.

$$\epsilon \sim \frac{m_{\text{susy}}}{M} \sim \frac{m_Z}{M} \ll 1$$

The corrections to the MSSM can be parametrized by operators suppressed by inverse powers of $M$; i.e. by powers of $\epsilon$. 
Assume that there is New Physics beyond the MSSM at a scale $M$, much above the electroweak scale $m_Z$ and the scale of the SUSY breaking terms $m_{\text{susy}}$. 

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The corrections to the MSSM can be parametrized by operators suppressed by inverse powers of $M$; i.e. by powers of $\epsilon$.

→ There can be significant effects from non-renormalizable terms on the same order as the one-loop terms.

We focus on an effective action analysis to the Higgs sector as an approach to consider the effects of New Physics Beyond the MSSM.

Brignole, Casas, Espinosa, Navarro, 03
Dine, Seiberg, Thomas, 07
Non-renormalizable operators

Remember the ordinary MSSM superpotential:

\[ W_{\text{MSSM}} \supset \int d^2 \theta \mu H_u H_d \]
Non-renormalizable operators

Remember the ordinary MSSM superpotential:

\[ W_{\text{MSSM}} \supset \int d^2 \theta \mu H_u H_d \]

There are only 2 operators at order \( \frac{1}{M} \):

\[ O_1 = \frac{1}{M} \int d^2 \theta (H_u H_d)^2 \]
\[ O_2 = \frac{1}{M} \int d^2 \theta Z (H_u H_d)^2 \]

\( Z \equiv \theta^2 m_{\text{susy}} \): spurion field
\( O_1 \): is a dimension 5 SUSY operator
\( O_2 \): parametrizes SUSY breaking

Both operators can lead to CP violation
BMSSM Higgs potential

Corrections to the MSSM Higgs potential

\[ \delta L = 2 \epsilon_1 H_u H_d \left( H_u^\dagger H_u + H_d^\dagger H_d \right) + \epsilon_2 (H_u H_d)^2 + \text{h.c.} \]
\[ + \frac{\epsilon_1}{\mu^*} \left[ 2(H_u H_d)(\tilde{H}_u \tilde{H}_d) + 2(\tilde{H}_u H_d)(H_u \tilde{H}_d) \right. \]
\[ \left. + (H_u \tilde{H}_d)(H_u \tilde{H}_d) + (\tilde{H}_u H_d)(\tilde{H}_u H_d) \right] + \text{h.c.} \]

where

\[ \epsilon_1 \equiv \frac{\mu^* \lambda_1}{M} \]
\[ \epsilon_2 \equiv -\frac{m_{\text{susy}} \lambda_2}{M} \]
BMSSM Higgs potential

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\[ + \frac{\epsilon_1}{\mu^*} \left[ 2(H_u H_d)(\tilde{H}_u \tilde{H}_d) + 2(\tilde{H}_u H_d)(H_u \tilde{H}_d) \right. \]
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* New contributions for Higgs boson masses
BMSSM Higgs potential

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\]

\[
+ \frac{\varepsilon_1}{\mu^*} \left[ 2(H_u H_d)(\tilde{H}_u \tilde{H}_d) + 2(\tilde{H}_u H_d)(H_u \tilde{H}_d)
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- New contributions for Higgs boson masses
- New contributions for higgsino ($\chi^0$ and $\chi^{\pm}$) masses
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**BMSSM Higgs potential**

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- New contributions for Higgs boson masses
- New contributions for higgsino ($\chi^0$ and $\chi^\pm$) masses
- New contributions for Higgs-higgsino couplings
BMSSM Higgs potential

 Corrections to the MSSM Higgs potential

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- New contributions for Higgs boson masses
- New contributions for higgsino (\(\chi^0\) and \(\chi^{\pm}\) masses)
- New contributions for Higgs-higgsino couplings

Vacuum stability: \(|\epsilon_1| \lesssim 0.1, |\epsilon_2| \lesssim 0.05\) see Blum, Delaunay, Hochberg, 09
Higgs spectrum

We consider the case where the NR operators can still be treated as perturbations:

\[
M_h^2 \simeq \left( m_h^{\text{tree}} \right)^2 + \delta_t m_h^2 + \delta_\epsilon m_h^2 \geq (114 \text{ GeV})^2
\]

\[
\delta_\epsilon m_h^2 = 2v^2 \left( \epsilon_2 - 2\epsilon_1 s_2\beta - \frac{2\epsilon_1 (m_A^2 + m_Z^2)s_2\beta + \epsilon_2 (m_A^2 - m_Z^2)c_2\beta}{\sqrt{(m_A^2 - m_Z^2)^2 + 4m_A^2 m_Z^2 s_2^2\beta}} \right)
\]

\[
\delta_\epsilon m_h^2 \sim \text{few dozens of GeVs!}
\]

The \( \delta_\epsilon m_h^2 \) relaxes the constraint in a significant way:
for \( \epsilon_1 \lesssim -0.1 \) and tan\( \beta \lesssim 5 \), light and unmixed stops allowed!
We consider the case where the NR operators can still be treated as perturbations:

\[
M_h^2 \simeq (m_h^{\text{tree}})^2 + \delta \tilde{t} m_h^2 + \delta \epsilon m_h^2 \gtrsim (114 \text{ GeV})^2
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→ The SUSY little hierarchy problem can be avoided
Higgs spectrum

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\]

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The \( \delta \epsilon m_h^2 \) relaxes the constraint in a significant way: for \( \epsilon_1 \lesssim -0.1 \) and \( \tan \beta \lesssim 5 \), light and unmixed stops allowed!

→ The SUSY little hierarchy problem can be avoided

Other Higgs masses also receive corrections...
The $\delta \epsilon m_h^2$ relaxes the constraint in a significant way: for $\epsilon_1 \lesssim -0.1$ and $\tan \beta \lesssim 5$, light and unmixed stops allowed!

$\rightarrow$ The SUSY little hierarchy problem can be avoided

Other Higgs masses also receive corrections...
**Higgsinos**

\[
M_{\chi^0} = \begin{pmatrix}
M_1 & 0 & -m_{Z\sigma} wc & m_{Z\sigma} s\beta \\
0 & M_2 & -m_{Z\rho} wc & -m_{Z\rho} s\beta \\
-m_{Z\sigma} wc & m_{Z\rho} wc & 0 & -\mu \\
m_{Z\sigma} s\rho & -m_{Z\rho} s\rho & -\mu & 0
\end{pmatrix} + \frac{4\epsilon_1 m_W^2}{\mu^* g^2} \begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & s_\beta^2 & s_{2\beta} \\
0 & 0 & s_{2\beta} & c_{\beta}^2
\end{pmatrix}
\]

The lightest neutralino \(\chi_1^0\) is a natural candidate for **cold dark matter**!

The NR operators also modify

- the chargino mass matrix
- Higgs-higgsino-higgsino & Higgs-Higgs-higgsino-higgsino couplings (DM annihilation cross sections)

Berg, Edsjö, Gondolo, Lundström, Sjörs, ‘09; NB, Blum, Losada, Nir, ‘09
Higgsinos

\[ M_{\chi^0} = \begin{pmatrix}
M_1 & 0 & -m_Z s_w c_\beta & m_Z s_w s_\beta \\
0 & M_2 & m_Z c_w c_\beta & -m_Z c_w s_\beta \\
-m_Z s_w c_\beta & m_Z c_w c_\beta & 0 & -\mu \\
m_Z s_w s_\beta & -m_Z c_w s_\beta & -\mu & 0
\end{pmatrix} + \frac{4\epsilon_1 m_W^2}{\mu^* g^2} \begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & s_\beta^2 & s_{2\beta} \\
0 & 0 & s_{2\beta} & c_\beta^2
\end{pmatrix} \]

The lightest neutralino \( \chi^0_1 \) is a natural candidate for cold dark matter!

The NR operators also modify

- the chargino mass matrix
- Higgs-higgsino-higgsino & Higgs-Higgs-higgsino-higgsino couplings (DM annihilation cross sections)

Berg, Edsjö, Gondolo, Lundström, Sjörs, ’09; NB, Blum, Losada, Nir, ‘09

→ Spectrum, dark matter relic density and DM detection rates are calculated using modified versions of SuSpect and micrOMEGAs
**Outline**

1. **Motivation**

2. **The BMSSM**

3. **Dark Matter**
   - Correlated stop-slepton masses
   - Light stops, heavy sleptons

4. **Dark Matter Direct Detection**

5. **Dark Matter Indirect Detection**
   - $\gamma$-rays
   - Positrons
   - Antiprotons

6. **Summary**
The mSUGRA model is specified by 5 parameters:

- \( \tan \beta \): ratio of the Higgs vevs
- \( m_{1/2} \): common mass for the gauginos (bino, wino and gluino)
- \( m_0 \): universal scalar mass (sfermions and Higgs bosons)
- \( A_0 \): universal trilinear coupling
- \( \text{sign } \mu \): sign of the \( \mu \) parameter

In mSUGRA scenarios usually the lightest neutralino is the LSP.

Because of the LEP constraint over the Higgs mass, the *bulk region* (i.e. low \( m_0 \) and low \( m_{1/2} \)) is ruled out.
Correlated stop-slepton masses

Let’s take: $A_0 = 0$ GeV, $\mu > 0$ and $\tan \beta = 3$

**mSUGRA**
Correlated stop-slepton masses

Let’s take: $A_0 = 0$ GeV, $\mu > 0$ and $\tan \beta = 3$

mSUGRA

• Regions excluded: $\tilde{\tau}$ LSP
Correlated stop-slepton masses

Let’s take: \( A_0 = 0 \) GeV, \( \mu > 0 \) and \( \tan \beta = 3 \)

**mSUGRA**

- Regions excluded: \( \tilde{\tau} \) LSP and \( \chi^\pm \) searches at LEP
**Correlated stop-slepton masses**

Let’s take: $A_0 = 0$ GeV, $\mu > 0$ and $\tan \beta = 3$

**mSUGRA**

- **Regions excluded:** $\tilde{\tau}$ LSP and $\chi^\pm$ searches at LEP
- **Bulk region:** LSP is mainly bino-like. DM relic density too high
Correlated stop-slepton masses

Let’s take: $A_0 = 0$ GeV, $\mu > 0$ and $\tan \beta = 3$

mSUGRA

- Regions excluded: $\tilde{\tau}$ LSP and $\chi^{\pm}$ searches at LEP
- Bulk region: LSP is mainly bino-like. DM relic density too high
- Regions fulfilling WMAP measurements:
  - Coannihilation with $\tilde{\tau}$
**Correlated stop-slepton masses**

Let’s take: $A_0 = 0$ GeV, $\mu > 0$ and $\tan \beta = 3$

**mSUGRA**

- **Regions excluded:** $\tilde{\tau}$ LSP and $\chi^\pm$ searches at LEP
- **Bulk region:** LSP is mainly bino-like. DM relic density too high
- **Regions fulfilling WMAP measurements:**
  - Coannihilation with $\tilde{\tau}$
  - Higgs- and Z-poles: $m_h \sim m_Z \sim 2m_\chi$ s-channel exchange

**Remark:**
- The BMSSM
- Dark Matter
- Direct Detection
- Indirect Detection
- Summary
Correlated stop-slepton masses

Let’s take: $A_0 = 0 \text{ GeV}$, $\mu > 0$ and $\tan \beta = 3$

- Regions excluded: $\tilde{\tau}$ LSP and $\chi^\pm$ searches at LEP
- Bulk region: LSP is mainly bino-like. DM relic density too high
- Regions fulfilling WMAP measurements:
  - Coannihilation with $\tilde{\tau}$
  - Higgs- and Z-poles: $m_h \sim m_Z \sim 2m_\chi$ s-channel exchange
- However $m_h \lesssim 105 \text{ GeV}$: The whole region is excluded!
Correlated stop-slepton masses

Let’s take: $A_0 = 0$ GeV, $\mu > 0$ and $\tan \beta = 3$  
$\epsilon_1 = -0.1$, $\epsilon_2 = 0$

mSUGRA

BMSSM mSUGRA-like

It should not be taken as an extended mSUGRA, but just as a framework specified at low energy.
Correlated stop-slepton masses

Let’s take: $A_0 = 0$ GeV, $\mu > 0$ and $\tan \beta = 3$ \hspace{1cm} $\epsilon_1 = -0.1$, $\epsilon_2 = 0$

$m_{1/2}$ [GeV] \hspace{1cm} $m_0$ [GeV]

It should not be taken as an extended mSUGRA, but just as a framework specified at low energy.

✔️ Important uplift of the Higgs mass → ‘bulk region’ re-opened
Correlated stop-slepton masses

Let’s take: \( A_0 = 0 \) GeV, \( \mu > 0 \) and \( \tan \beta = 3 \quad \epsilon_1 = -0.1, \epsilon_2 = 0 \)

**mSUGRA**

**BMSSM mSUGRA-like**

It should not be taken as an extended mSUGRA, but just as a framework specified at low energy.

- Important uplift of the Higgs mass → ‘bulk region’ re-opened
- New region fulfilling DM constraint: Higgs-funnel
Correlated stop-slepton masses

Let’s take: \( A_0 = 0 \text{ GeV}, \mu > 0 \) and \( \tan\beta = 3 \) \( \epsilon_1 = -0.1, \epsilon_2 = 0 \)

It should not be taken as an extended mSUGRA, but just as a framework specified at low energy.

- **Important uplift of the Higgs mass** → ‘bulk region’ re-opened
- New region fulfilling DM constraint: Higgs-funnel
- \( \chi_1^0 \) bino-like: marginal impact on \( m_\chi \) and ann. cross section
Light stops, heavy sleptons

Now we consider a low-energy scenario giving rise to light stops

- $\tan \beta$: ratio of the Higgs vevs
- $\mu$: higgsino mass parameter
- $m_A$: pseudoscalar Higgs mass parameter
- $X_t$: trilinear coupling for stops, $X_t = A_t - \mu / \tan \beta$
- $M_2$: wino mass parameter, $M_1 \sim \frac{1}{2} M_2$
- $m_U$: stop right mass parameter
- $m_Q$: 3rd generation squarks left mass parameter
- $m_{\tilde{f}}$: mass for sleptons, 1st and 2nd gen. squarks and $\tilde{b}_R$

$m_U = 210 \text{ GeV}, \quad X_t = 0 \text{ GeV}, \quad m_Q = m_{\tilde{f}} = m_A = 500 \text{ GeV}$
Light stops, heavy sleptons

Now we consider a low-energy scenario giving rise to light stops

- \( \tan \beta \): ratio of the Higgs vevs
- \( \mu \): higgsino mass parameter
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- \( m_U \): stop right mass parameter
- \( m_Q \): 3\textsuperscript{rd} generation squarks left mass parameter
- \( m_{\tilde{f}} \): mass for sleptons, 1\textsuperscript{st} and 2\textsuperscript{nd} gen. squarks and \( \tilde{b}_R \)

\[ m_U = 210 \text{ GeV}, \quad X_t = 0 \text{ GeV}, \quad m_Q = m_{\tilde{f}} = m_A = 500 \text{ GeV} \]

\[ m_{\tilde{t}_1} \lesssim 150 \text{ GeV}, \quad 370 \text{ GeV} \lesssim m_{\tilde{t}_2} \lesssim 400 \text{ GeV} \]

A scenario with light unmixed stops is ruled out in the MSSM
Motivation | The BMSSM | Dark Matter | Direct Detection | Indirect Detection | Summary
---|---|---|---|---|---

**Light stops, heavy sleptons**

**MSSM**

\[ \tan \beta = 3, \; \epsilon_1 = 0, \; \epsilon_2 = 0 \]

Diagram showing the parameter space of MSSM with constraints from WMAP and stability conditions.
Light stops, heavy sleptons

MSSM
\[ \tan \beta = 3, \quad \epsilon_1 = 0, \quad \epsilon_2 = 0 \]

- Regions excluded: \( \tilde{t} \) LSP
Light stops, heavy sleptons

MSSM
\[ \tan \beta = 3, \ e_1 = 0, \ e_2 = 0 \]

- Regions excluded: \( \tilde{t} \) LSP and \( \chi^\pm \) searches at LEP
**Light stops, heavy sleptons**

**MSSM**
\[ \tan \beta = 3, \quad \epsilon_1 = 0, \quad \epsilon_2 = 0 \]

- Regions excluded: \( \tilde{t} \) LSP and \( \chi^{\pm} \) searches at LEP
- Regions fulfilling WMAP measurements:
  - Coannihilation with \( \tilde{t} \): \( \chi \tilde{t} \rightarrow Wb, tg \quad \tilde{t}\tilde{t} \rightarrow gg \)
Light stops, heavy sleptons

**MSSM**

\[
\text{tan } \beta = 3, \; \epsilon_1 = 0, \; \epsilon_2 = 0
\]

- Regions excluded: \( \tilde{t} \) LSP and \( \chi^{\pm} \) searches at LEP
- Regions fulfilling WMAP measurements:
  - Coannihilation with \( \tilde{t} \): \( \chi \tilde{t} \rightarrow Wb, t g \) \( \tilde{t} \tilde{t} \rightarrow gg \)
  - Higgs- and Z-poles: \( m_h \sim m_Z \sim 2m_\chi \) \( s \)-channel exchange
Light stops, heavy sleptons

- Regions excluded: $\tilde{t}$ LSP and $\chi^{\pm}$ searches at LEP
- Regions fulfilling WMAP measurements:
  - Coannihilation with $\tilde{t}$: $\chi\tilde{t} \rightarrow Wb, tg \quad \tilde{t}\tilde{t} \rightarrow gg$
  - Higgs- and Z-poles: $m_h \sim m_Z \sim 2m_\chi$  \(s\)-channel exchange
- However $m_h \lesssim 85$ GeV: The whole region is excluded!
**Light stops, heavy sleptons**

**MSSM**
\[ \tan \beta = 3, \quad \varepsilon_1 = 0, \quad \varepsilon_2 = 0 \]

**BMSSM**
\[ \tan \beta = 3, \quad \varepsilon_1 = -0.1, \quad \varepsilon_2 = 0 \]

**Important uplift of the Higgs mass:** \( m_h \sim 122 \text{ GeV} \)
**Motivation**

- The BMSSM
- Dark Matter
- Direct Detection
- Indirect Detection
- Summary

## Light stops, heavy sleptons

### MSSM

**tan \( \beta = 3 \), \( \epsilon_1 = 0 \), \( \epsilon_2 = 0 \)**

### BMSSM

**tan \( \beta = 3 \), \( \epsilon_1 = -0.1 \), \( \epsilon_2 = 0 \)**

- **WMAP**
- \( \tilde{\tau}_1 \) LSP
- LEP
- V. stability

- ✔️ *Important uplift of the Higgs mass: \( m_h \sim 122 \text{ GeV} \)*
- ✗ NR operators destabilize scalar potential: vacuum metastable
**Motivation**

- The BMSSM
- Dark Matter
- Direct Detection
- Indirect Detection
- Summary

---

**Light stops, heavy sleptons**

**MSSM**

\[
\tan \beta = 3, \; \varepsilon_1 = 0, \; \varepsilon_2 = 0
\]

**BMSSM**

\[
\tan \beta = 3, \; \varepsilon_1 = -0.1, \; \varepsilon_2 = 0
\]

- **Important uplift of the Higgs mass:** \( m_h \sim 122 \text{ GeV} \)
- **NR operators destabilize scalar potential:** vacuum metastable
- **New region fulfilling DM constraint:** Higgs-funnel
Light stops, heavy sleptons

**MSSM**
\[\tan \beta = 3, \varepsilon_1 = 0, \varepsilon_2 = 0\]

**BMSSM**
\[\tan \beta = 3, \varepsilon_1 = -0.1, \varepsilon_2 = 0\]

- **Important uplift of the Higgs mass**: \(m_h \sim 122\) GeV
- **NR operators destabilize scalar potential**: vacuum metastable
- **New region fulfilling DM constraint**: Higgs-funnel
- **Sizable impact on** \(m_\chi\) **and ann. cross section**
  when \(\chi^0_1\) is higgsino-like
### Outline

1. **Motivation**
2. **The BMSSM**
3. **Dark Matter**
   - Correlated stop-slepton masses
   - Light stops, heavy sleptons
4. **Dark Matter Direct Detection**
5. **Dark Matter Indirect Detection**
   - $\gamma$-rays
   - Positrons
   - Antiprotons
6. **Summary**
Direct detection experiments are designed to detect dark matter particles by their elastic collision with target nuclei, placed in a detector on the Earth.

XENON

Exposures: $\varepsilon = 30, 300, 3000 \text{ kg} \cdot \text{year}$
Xenon1T and 11 days, 4 months or 3 years
Direct detection experiments are designed to detect dark matter particles by their elastic collision with target nuclei, placed in a detector on the Earth.

Xenon discriminates signal from background by simultaneous measurements of:
- scintillation
- ionization

The collaboration expects to have a negligible background.

→ 7 energy bins between [4, 30] keV

Detectability definition:

\[
\chi^2 = \sum_{i=1}^{7} \frac{(N_{i}^{\text{tot}} - N_{i}^{\text{bkg}})^2}{N_{i}^{\text{tot}}}
\]
Direct detection experiments are designed to detect **dark matter particles** by their **elastic collision with target nuclei**, placed in a detector on the Earth.

### Recoil rates

\[
\frac{dN}{dE_r} = \frac{\sigma_{\chi-p} \cdot \rho_0}{2 M_r^2 m_\chi} F(E_r)^2 \int_{v_{\min}(E_r)}^{v_{\text{esc}}} \frac{f(v)}{v} dv
\]

Reduced mass \( M_r = \frac{m_\chi m_N}{m_\chi + m_N} \)

- \( N \): number of scatterings \((s^{-1}kg^{-1})\)
- \( E_r \): nuclear recoil energy \(~\text{few keV}\)
- \( m_\chi \): WIMP mass
- \( \sigma_{\chi-p} \): WIMP-proton scattering cross-section
- Assume pure **spin-independent** coupling

\( \rho_0 \): local WIMP density \(0.38 \text{ GeV cm}^{-3}\)

\( F \): nuclear form factor Woods-Saxon

\( f(v) \): WIMP local vel. distribution \(\text{M.B.}\)

\[
f(v) = \frac{1}{\sqrt{\pi}} \frac{v}{1.05 v_0^2} \left[ e^{-(v-1.05 v_0)^2/v_0^2} - e^{-(v+1.05 v_0)^2/v_0^2} \right]
\]

---

**XENON**

Exposures: \( \varepsilon = 30, 300, 3000 \text{ kg \cdot year}\)

Xenon1T and 11 days, 4 months or 3 years
Correlated stop-slepton masses

**mSUGRA**

\[ \tan \beta = 3, \ e_1 = 0, \ e_2 = 0 \]

Exclusion lines: ability to test and exclude at 95% CL
Correlated stop-slepton masses

mSUGRA
\[ \tan \beta = 3, \ \varepsilon_1 = 0, \ \varepsilon_2 = 0 \]

Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low \( m_0 \) and \( m_{1/2} \) values
  \( m_0 \rightarrow \text{increase squark masses}, \ m_{1/2} \rightarrow \text{increase LSP mass} \)
Correlated stop-slepton masses

**mSUGRA**

\[
\tan \beta = 3, \ \varepsilon_1 = 0, \ \varepsilon_2 = 0
\]

Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low \( m_0 \) and \( m_{1/2} \) values
- For low \( m_{1/2} \), LSP tends to be a higgsino-bino mixed state \( (C_{\chi\chi h}) \)
Correlated stop-slepton masses

Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low $m_0$ and $m_{1/2}$ values
- For low $m_{1/2}$, LSP tends to be a higgsino-bino mixed state ($C_{\chi\chi h}$)
- Detection maximised for low $\tan \beta$, $C_{\chi\chi h} \propto \sin 2\beta$ ($|\mu| \gg M_1$)
Correlated stop-slepton masses

Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low $m_0$ and $m_{1/2}$ values
- For low $m_{1/2}$, LSP tends to be a higgsino-bino mixed state ($C_{\chi\chi h}$)
- Detection maximised for low $\tan \beta$, $C_{\chi\chi h} \propto \sin 2\beta$ ($|\mu| \gg M_1$)
- Sizable amount of the parameter space can be probed
Motivation

The BMSSM

Dark Matter

Direct Detection

Indirect Detection

Summary

Correlated stop-slepton masses

$m_{SUGRA}$

$m_{SUGRA}$-like

Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low $m_0$ and $m_{1/2}$ values
- For low $m_{1/2}$, LSP tends to be a higgsino-bino mixed state ($C_{\chi\chi h}$)
- Detection maximised for low $\tan \beta$, $C_{\chi\chi h} \propto \sin 2\beta$ ($|\mu| \gg M_1$)
- Sizable amount of the parameter space can be probed
- NR operators $\rightarrow$ deterioration of the detection: $m_h$
- But without NR operators, the parameter space was excluded!
Light stops, heavy sleptons

Exclusion lines: ability to test and exclude at 95% CL
Light stops, heavy sleptons

MSSM
\[ \tan \beta = 3, \; \epsilon_1 = 0, \; \epsilon_2 = 0 \]

Exclusion lines: ability to test and exclude at 95% CL

- Partially ruled out by first results from Xenon100!
**Light stops, heavy sleptons**

**MSSM**

\[ \tan \beta = 3, \quad \epsilon_1 = 0, \quad \epsilon_2 = 0 \]

Exclusion lines: ability to test and exclude at 95% CL

- Partially ruled out by first results from Xenon100!
- Detection prospects maximised for low \( \mu \) and/or \( M_1 \): light LSP
Light stops, heavy sleptons

MSSM
\[ \tan \beta = 3, \ \varepsilon_1 = 0, \ \varepsilon_2 = 0 \]

Exclusion lines: ability to test and exclude at 95% CL

- Partially ruled out by first results from Xenon100!
- Detection prospects maximised for low \( \mu \) and/or \( M_1 \): light LSP
- Scattering cross section enhanced near \( \mu \sim M_1 \) \( (C_{\chi h}, C_{\chi H}) \)
Light stops, heavy sleptons

MSSM
\[\tan \beta = 3, \ \varepsilon_1 = 0, \ \varepsilon_2 = 0\]

Exclusion lines: ability to test and exclude at 95% CL

- Partially ruled out by first results from Xenon100!
- Detection prospects maximised for low \(\mu\) and/or \(M_1\): light LSP
- Scattering cross section enhanced near \(\mu \sim M_1\) \((C_{\chi \chi h}, C_{\chi \chi H})\)
- Neither Z- nor h-funnel enhance SI direct detection

Spin-dependent detection sensible to the Z-peak (non-universality)
Motivation

The BMSSM

Dark Matter

Direct Detection

Indirect Detection

Summary

Light stops, heavy sleptons

Exclusion lines: ability to test and exclude at 95% CL

- Partially ruled out by first results from Xenon100!
- Detection prospects maximised for low $\mu$ and/or $M_1$: light LSP
- Scattering cross section enhanced near $\mu \sim M_1$ ($C_{\chi\chi h}$, $C_{\chi\chi H}$)
- Neither $Z$- nor $h$-funnel enhance SI direct detection
- NR operators deteriorates DD: increase $m_h$ and suppression $C_{\chi\chi h}$
Motivation
The BMSSM
Dark Matter
Direct Detection
Indirect Detection
Summary

Light stops, heavy sleptons

Exclusion lines: ability to test and exclude at 95% CL

✗ Partially ruled out by first results from Xenon100!
• Detection prospects maximised for low $\mu$ and/or $M_1$: light LSP
• Scattering cross section enhanced near $\mu \sim M_1$ ($C_{XXh}$, $C_{XXH}$)
• Neither $Z$- nor $h$-funnel enhance SI direct detection
⇒ NR operators deteriorates DD: increase $m_h$ and suppression $C_{XXh}$
✓ BMSSM satisfies all DD measurements!
Outline

1 Motivation
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4 Dark Matter Direct Detection
5 Dark Matter Indirect Detection
   - $\gamma$-rays
   - Positrons
   - Antiprotons
6 Summary
We study the ability of **Fermi** to identify **Gamma-rays** generated in **DM annihilation** in the galactic center

$$\chi \bar{\chi} \rightarrow b \bar{b}, \ WW \cdots \rightarrow \gamma + \ldots$$
Dark matter indirect detection (γ-rays)

We study the ability of Fermi to identify Gamma-rays generated in DM annihilation in the galactic center

\[ \chi \bar{\chi} \rightarrow b\bar{b}, \; WW \cdots \rightarrow \gamma + \ldots \]
Dark matter indirect detection (γ-rays)

We study the ability of Fermi to identify Gamma-rays generated in DM annihilation in the galactic center

$$\chi \bar{\chi} \rightarrow b \bar{b}, \ W W \cdots \rightarrow \gamma + \ldots$$
Dark matter indirect detection ($\gamma$-rays)

We study the ability of Fermi to identify Gamma-rays generated in DM annihilation in the galactic center

$$\chi\bar{\chi} \rightarrow b\bar{b}, \; WW \cdots \rightarrow \gamma + \ldots$$

Fermi telescope (Launched ‘08)
We study the ability of Fermi to identify Gamma-rays generated in DM annihilation in the galactic center:

$$\chi\bar{\chi} \rightarrow b\bar{b}, \ WW \cdots \rightarrow \gamma + \ldots$$

**Differential event rate**

$$\Phi_\gamma(E_\gamma, \psi) = \sum_i \frac{dN_{\gamma}^i}{dE_\gamma} \langle \sigma v \rangle \frac{1}{8\pi m_\chi^2} \int_{\text{los}} \rho(r)^2 dl$$

- $dN/dE$: spectrum of secondary particles
- $E_\gamma$: gamma energy
- $\langle \sigma v \rangle$: averaged annihilation cross-section by velocity
- $\rho(r)$: dark matter halo profile

5-years data acquisition, $\Delta\Omega = 3 \cdot 10^{-5}$ sr

Background: HESS measurements (Diffuse Galactic emission and Sagittarius A*)
Dark matter indirect detection ($\gamma$-rays)

We study the ability of Fermi to identify Gamma-rays generated in DM annihilation in the galactic center

$$\chi\bar{\chi} \rightarrow b\bar{b}, \ WW \cdots \rightarrow \gamma + \ldots$$

Fermi telescope (Launched ‘08)

Differential event rate

$$\Phi_\gamma(E_\gamma, \psi) = \sum_i \frac{dN^i_\gamma}{dE_\gamma} \langle \sigma_i v \rangle \frac{1}{8\pi m_\chi^2} \int_{\text{los}} \rho(r)^2 \, dl$$

$dN/dE$: spectrum of secondary particles
$E_\gamma$: gamma energy
$\langle \sigma v \rangle$: averaged annihilation cross-section by velocity
$\rho(r)$: dark matter halo profile
We study the ability of Fermi to identify Gamma-rays generated in DM annihilation in the galactic center

\[ \chi \bar{\chi} \rightarrow b \bar{b}, \; WW \cdots \rightarrow \gamma + \ldots \]

\[ \Phi_\gamma(E_\gamma, \psi) = \sum_i \frac{dN^i_\gamma}{dE_\gamma} \langle \sigma_i v \rangle \frac{1}{8\pi m_\chi^2} \int_{\text{los}} \rho(r)^2 dl \]

- \( dN/dE \): spectrum of secondary particles
- \( E_\gamma \): gamma energy
- \( \langle \sigma v \rangle \): averaged annihilation cross-section by velocity
- \( \rho(r) \): dark matter halo profile

3 halo profiles: Einasto, NFW and NFW\(_c\) (adiabatic compression due to baryons)
**Correlated stop-slepton masses**

**mSUGRA**

\[
\tan \beta = 3, \quad \varepsilon_1 = 0, \quad \varepsilon_2 = 0
\]

Exclusion lines: ability to test and exclude at 95% CL
Correlated stop-slepton masses

Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low $m_0$ and $m_{1/2}$
Correlated stop-slepton masses

Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low $m_0$ and $m_{1/2}$
- Thresholds: $\chi\chi \rightarrow W^+W^-$, $\chi\chi \rightarrow t\bar{t}$
Motivation

The BMSSM

Dark Matter

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Indirect Detection

Summary

Correlated stop-slepton masses

$m_{1/2}$ [GeV]

$m_0$ [GeV]

$\tan \beta = 3, \varepsilon_1 = 0, \varepsilon_2 = 0$

$\varepsilon_1 = -0.1, \varepsilon_2 = 0$

Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low $m_0$ and $m_{1/2}$
- Thresholds: $\chi\chi \rightarrow W^+W^-$, $\chi\chi \rightarrow t\bar{t}$
- Detection maximised for high $\tan \beta$ $\chi\chi \rightarrow b\bar{b}$ and $\tau\tau \propto \tan \beta$ and $1/\cos \beta$
Correlated stop-slepton masses

![Graph showing correlated stop-slepton masses](image)

Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low $m_0$ and $m_{1/2}$
- Thresholds: $\chi\chi \rightarrow W^+ W^-$, $\chi\chi \rightarrow t\bar{t}$
- Detection maximised for high $\tan\beta$ $\chi\chi \rightarrow b\bar{b}$ and $\tau\tau \sim \tan\beta$ and $1/\cos\beta$
- For large $\tan\beta$ thresholds weaken
**Correlated stop-slepton masses**

Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low $m_0$ and $m_{1/2}$
- Thresholds: $\chi\chi \to W^+W^-$, $\chi\chi \to t\bar{t}$
- Detection maximised for high $\tan\beta$ $\chi\chi \to b\bar{b}$ and $\tau\tau \propto \tan\beta$ and $1/\cos\beta$
- For large $\tan\beta$ thresholds weaken
- Only scenarios with highly cusped inner regions could be probed
Correlated stop-slepton masses

**mSUGRA**
- \(\tan \beta = 3, \ \varepsilon_1 = 0, \ \varepsilon_2 = 0\)

**BMSSM mSUGRA-like**
- \(\tan \beta = 3, \ \varepsilon_1 = -0.1, \ \varepsilon_2 = 0\)

Exclusion lines: ability to test and exclude at 95% CL

- Detection prospects maximised for low \(m_0\) and \(m_{1/2}\)
- Thresholds: \(\chi\chi \rightarrow W^+ W^-\), \(\chi\chi \rightarrow t\bar{t}\)
- Detection maximised for high \(\tan \beta\)  \(\chi\chi \rightarrow b\bar{b}\) and \(\tau\tau \propto \tan \beta\) and \(1/\cos \beta\)
- For large \(\tan \beta\) thresholds weaken
- Only scenarios with highly cusped inner regions could be probed
- NR operators: Higgs pole ‘invisible’ (\(\nu \rightarrow 0\))
Light stops, heavy sleptons

Exclusion lines: ability to test and exclude at 95% CL
Light stops, heavy sleptons

Exclusion lines: ability to test and exclude at 95% CL

- Detection enhanced for $M_1 \gg \mu$ ($\chi\chi Z$ and $\chi\chi^\pm W^\mp$ couplings)
Light stops, heavy sleptons

Exclusion lines: ability to test and exclude at 95% CL

- Detection enhanced for $M_1 \gg \mu$  ($\chi\chi Z$ and $\chi\chi^\pm W^\mp$ couplings)
- $\langle \sigma v \rangle$ enhanced for high $\tan \beta$  ($\chi\chi \to b\bar{b}, WW$)
**Light stops, heavy sleptons**

Exclusion lines: ability to test and exclude at 95% CL

- Detection enhanced for $M_1 \gg \mu$ (χχZ and χχ±W∓ couplings)
- $\langle \sigma v \rangle$ enhanced for high tan$\beta$ (χχ $\rightarrow b\bar{b}$, WW)
- $h$-funnel could not be tested (no s-wave contribution)
Light stops, heavy sleptons

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- $h$-funnel could not be tested (no s-wave contribution)
- NFW and Einasto could test some regions, but not relevant
Antimatter \((e^+ \text{ and } \bar{p})\) propagation

- Diffusion equation solved in the Diffusive zone
  - Baltz & Edsjö ’98; Lavalle, Pochon, Salati & Taillet ’06

\[
\frac{\partial f}{\partial t} = K(E) \nabla^2 f + Q_{\text{inj}} + \frac{\partial}{\partial E} [b(E)f] - 2h \delta(z) \Gamma_{\text{ann}}f - \frac{\partial}{\partial z} [V_c f]
\]

- diffusion
- source
- energy loss
- spallation
- convective wind
Light stops, heavy sleptons - Positrons

**MSSM**

- $\tan \beta = 3, \ \epsilon_1 = 0, \ \epsilon_2 = 0$

**BMSSM**

- $\tan \beta = 3, \ \epsilon_1 = -0.1, \ \epsilon_2 = 0$

---

Perspectives for the oncoming AMS-02 satellite

- Background: Fermi & PAMELA measurements.
- PAMELA's 'heritage': A quite large background that is difficult to overcome.
- PAMELA excess buries all signals
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**Motivation**

The BMSSM

Dark Matter

Direct Detection

Indirect Detection

Summary

**Light stops, heavy sleptons - Antiprotons**

**Perspectives for the oncoming AMS-02 satellite**

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Outline

1. Motivation
2. The BMSSM
3. Dark Matter
   - Correlated stop-slepton masses
   - Light stops, heavy sleptons
4. Dark Matter Direct Detection
5. Dark Matter Indirect Detection
   - $\gamma$-rays
   - Positrons
   - Antiprotons
6. Summary
Conclusions and prospects

- NR operators in the Higgs sector introduced for reducing fine-tuning (Little hierarchy)
- Bulk region re-opened
- Possible to have light unmixed stops
- New regions fulfilling the DM constraint:
  - Higgs-pole
  - Higgs-stop coannihilation
- EW baryogenesis opens up
- Both scenarios could be tested by present machines!
- Complementarity with different detection modes
Antimatter propagation

\[
\frac{\partial f}{\partial t} = K(E) \nabla^2 f
\]

Diffusion equation

\[
K(E) = K_0 E_{\text{GeV}}^\alpha
\]

Diffusion coefficient

Propagation parameters \(K_0\) and \(\alpha\) fixed by N-body simulations
Antimatter propagation

\[ \frac{\partial f}{\partial t} = K(E) \nabla^2 f + Q_{\text{inj}} \]

→ Source term due to DM DM annihilation

\[ Q_{\text{inj}} = \frac{1}{2} \left( \frac{\rho(r)}{m_\chi} \right)^2 \sum_k \langle \sigma v \rangle_k \frac{d N_k}{dE} \]
Antimatter propagation

\[ \frac{\partial f}{\partial t} = K(E) \nabla^2 f + Q_{\text{inj}} + \frac{\partial}{\partial E} [b(E)f] \]

→ Energy loss term

\[ b(E) = \frac{E^2_{\text{GeV}}}{\tau_E} \]  
Energy loss rate

For antiprotons energy losses can be ignored
**Antimatter propagation**

\[
\frac{\partial f}{\partial t} = K(E) \nabla^2 f + Q_{\text{inj}} + \frac{\partial}{\partial E} [b(E)f] - 2h \delta(z) \Gamma_{\text{ann}} f
\]

- Annihilation of \( \bar{p} \) on interstellar protons in the galactic plane (Spallation)

\[
\Gamma_{\text{ann}} = \left( n_H + 4^{2/3} n_{He} \right) \sigma_{\text{ann}}^{p\bar{p}} v_{\bar{p}} \quad \text{Annihilation rate}
\]

Annihilation only relevant for antiprotons
Antimatter propagation

\[ \frac{\partial f}{\partial t} = K(E) \nabla^2 f + Q_{\text{inj}} + \frac{\partial}{\partial E} [b(E)f] - 2h \delta(z) \Gamma_{\text{ann}} f \]

→ Final Diffusion equation

Semi-analytical 2D diffusion equation

Baltz & Edsjö ’98; Lavalle, Pochon, Salati & Taillet ’06

picture snatched to M. Cirelli
Positrons from PAMELA

- Steep $e^+$ excess above 10 GeV
- Very large flux