Dark Matter at the LHC: A Window on the GUT Scale

Jonathan Roberts

IFT, Warsaw

27/9/07, "UniverseNet": The Origin of the Universe

SUSY's dark secret

The lightest MSSM neutralino is a mixture of the bino, wino and higgsinos.

SUSY's dark secret

The lightest MSSM neutralino is a mixture of the bino, wino and higgsinos. Unfortunately:

SUSY's dark secret

The lightest MSSM neutralino is a mixture of the bino, wino and higgsinos. Unfortunately:

- Bino($\tilde{B}$) Dark Matter: Generally gives $\Omega_{CDM} h^2 \gg \Omega_{CDM}^{WMAP} h^2$

SUSY's dark secret

The lightest MSSM neutralino is a mixture of the bino, wino and higgsinos. Unfortunately:

- Bino($\tilde{B}$) Dark Matter: Generally gives $\Omega_{CDM}h^2 \gg \Omega_{CDM}^{WMAP}h^2$
- Wino or Higgsino ($\tilde{W}$,$\tilde{h}$) Dark Matter: Generally gives $\Omega_{CDM}h^2 \ll \Omega_{CDM}^{WMAP}h^2$

SUSY's dark secret

The lightest MSSM neutralino is a mixture of the bino, wino and higgsinos. Unfortunately:

- Bino($\tilde{B}$) Dark Matter: Generally gives $\Omega_{CDM} h^2 \gg \Omega_{CDM}^{WMAP} h^2$
- Wino or Higgsino ($\tilde{W}$,$\tilde{h}$) Dark Matter: Generally gives $\Omega_{CDM} h^2 \ll \Omega_{CDM}^{WMAP} h^2$

Therefore the MSSM "naturally" gives the wrong dark matter density...

SUSY's dark secret

The lightest MSSM neutralino is a mixture of the bino, wino and higgsinos. Unfortunately:

- Bino($\tilde{B}$) Dark Matter: Generally gives $\Omega_{CDM}h^2 \gg \Omega_{CDM}^{WMAP}h^2$
- Wino or Higgsino ($\tilde{W}$,$\tilde{h}$) Dark Matter: Generally gives $\Omega_{CDM}h^2 \ll \Omega_{CDM}^{WMAP}h^2$

Therefore the MSSM "naturally" gives the wrong dark matter density...

There are 2 solutions within the MSSM:

SUSY's dark secret

The lightest MSSM neutralino is a mixture of the bino, wino and higgsinos. Unfortunately:

- Bino($\tilde{B}$) Dark Matter: Generally gives $\Omega_{CDM}h^2 \gg \Omega_{CDM}^{WMAP}h^2$
- Wino or Higgsino ($\tilde{W}$,$\tilde{h}$) Dark Matter: Generally gives $\Omega_{CDM}h^2 \ll \Omega_{CDM}^{WMAP}h^2$

Therefore the MSSM "naturally" gives the wrong dark matter density...

There are 2 solutions within the MSSM:

1. Add **just enough** Wino or Higgsino into Bino dark matter.

SUSY's dark secret

The lightest MSSM neutralino is a mixture of the bino, wino and higgsinos. Unfortunately:

- Bino($\tilde{B}$) Dark Matter: Generally gives $\Omega_{CDM}h^2 \gg \Omega_{CDM}^{WMAP}h^2$
- Wino or Higgsino ($\tilde{W}$,$\tilde{h}$) Dark Matter: Generally gives $\Omega_{CDM}h^2 \ll \Omega_{CDM}^{WMAP}h^2$

Therefore the MSSM "naturally" gives the wrong dark matter density...

There are 2 solutions within the MSSM:

1. Add **just enough** Wino or Higgsino into Bino dark matter.
2. Enhance an annihilation channel **just enough** for Bino dark matter to account for the observed relic density.

SUSY's dark secret

The lightest MSSM neutralino is a mixture of the bino, wino and higgsinos. Unfortunately:

- Bino($\tilde{B}$) Dark Matter: Generally gives $\Omega_{CDM}h^2 \gg \Omega_{CDM}^{WMAP}h^2$
- Wino or Higgsino ($\tilde{W}$,$\tilde{h}$) Dark Matter: Generally gives $\Omega_{CDM}h^2 \ll \Omega_{CDM}^{WMAP}h^2$

Therefore the MSSM "naturally" gives the wrong dark matter density...

There are 2 solutions within the MSSM:

1. Add **just enough** Wino or Higgsino into Bino dark matter.
2. Enhance an annihilation channel **just enough** for Bino dark matter to account for the observed relic density.

This sounds like fine-tuning.

How bad is this for the MSSM?

- SUSY is directly motivated by considerations of naturalness

How bad is this for the MSSM?

- SUSY is directly motivated by considerations of naturalness as it solves the hierarchy problem of the standard model.

How bad is this for the MSSM?

- SUSY is directly motivated by considerations of naturalness as it solves the hierarchy problem of the standard model.
- Lots of people have claimed that SUSY naturally accounts for dark matter.

How bad is this for the MSSM?

- SUSY is directly motivated by considerations of naturalness as it solves the hierarchy problem of the standard model.
- Lots of people have claimed that SUSY naturally accounts for dark matter.

So what options do we have?

How bad is this for the MSSM?

- SUSY is directly motivated by considerations of naturalness as it solves the hierarchy problem of the standard model.
- Lots of people have claimed that SUSY naturally accounts for dark matter.

So what options do we have?

- Give up on naturalness as a criteria.

How bad is this for the MSSM?

- SUSY is directly motivated by considerations of naturalness as it solves the hierarchy problem of the standard model.
- Lots of people have claimed that SUSY naturally accounts for dark matter.

So what options do we have?

- Give up on naturalness as a criteria.
  - Throw away our map and compass and lose ourselves in the (anthropic) landscape...

How bad is this for the MSSM?

- SUSY is directly motivated by considerations of naturalness as it solves the hierarchy problem of the standard model.
- Lots of people have claimed that SUSY naturally accounts for dark matter.

So what options do we have?

- Give up on naturalness as a criteria.
    - Throw away our map and compass and lose ourselves in the (anthropic) landscape...
- or quantify the degree of fine-tuning involved.

How bad is this for the MSSM?

- SUSY is directly motivated by considerations of naturalness as it solves the hierarchy problem of the standard model.
- Lots of people have claimed that SUSY naturally accounts for dark matter.

So what options do we have?

- Give up on naturalness as a criteria.
  - Throw away our map and compass and lose ourselves in the (anthropic) landscape...
- or quantify the degree of fine-tuning involved.

... and remember that the MSSM is an effective theory.

Quantifying fine-tuning

We need a quantitative measure of fine-tuning.

Quantifying fine-tuning

We need a quantitative measure of fine-tuning.

Ellis and Olive introduced an analagous measure to the one used to measure the fine-tuning required for electroweak symmetry breaking:

$$\Delta_a^{\Omega} = \left| \frac{\partial \ln \left(\Omega_{CDM} h^2 \right)}{\partial \ln \left(a \right)} \right|$$

Quantifying fine-tuning

We need a quantitative measure of fine-tuning.

Ellis and Olive introduced an analagous measure to the one used to measure the fine-tuning required for electroweak symmetry breaking:

$$\Delta_a^\Omega = \left| \frac{\partial \ln \left(\Omega_{CDM} h^2 \right)}{\partial \ln (a)} \right|$$

If $\Delta_a^\Omega = 100$, a 1% change in a gives a 100% change in $\Omega_{CDM} h^2$.

The Constrained Minimal Supersymmetric Standard Model (CMSSM)

The CMSSM is one of the simplest SUSY models.

The Constrained Minimal Supersymmetric Standard Model (CMSSM)

The CMSSM is one of the simplest SUSY models.

Instead of the many (> 100) parameters of the MSSM, we have:

$$a_{CMSSM} \in \{m_0,\ m_{1/2},\ \tan\beta,\ A_0,\ \mathrm{sign}(\mu)\}$$

The Constrained Minimal Supersymmetric Standard Model (CMSSM)

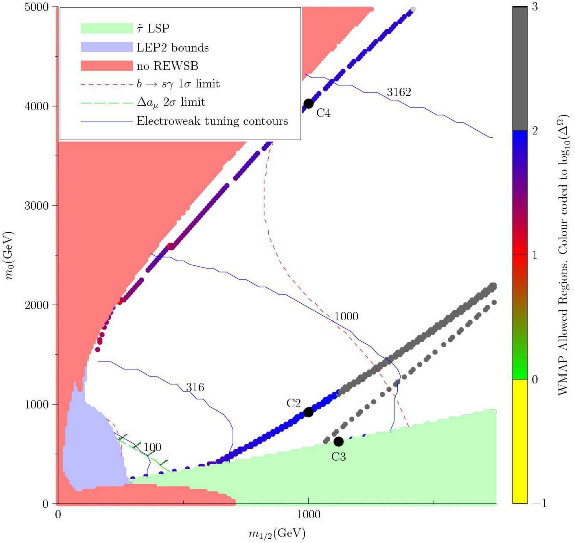
The CMSSM is one of the simplest SUSY models.

Instead of the many (> 100) parameters of the MSSM, we have:

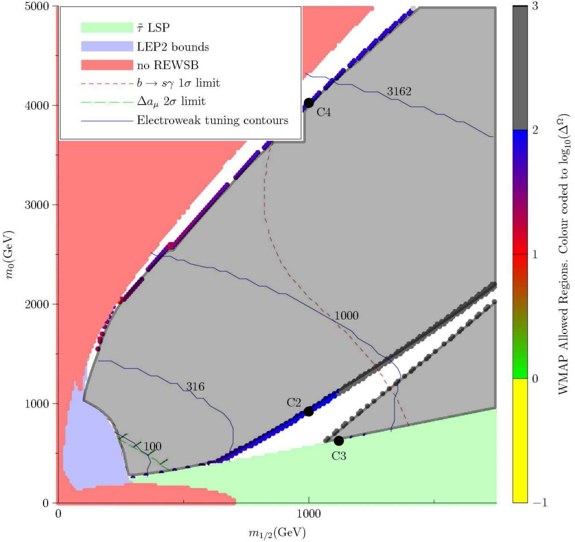
$$a_{CMSSM} \in \left\{ m_0,\ m_{1/2},\ \tan\beta,\ A_0,\ \mathrm{sign}(\mu) \right\}$$

The masses are set at m_{GUT} and run (using `SoftSusy`) to m_{EW}.

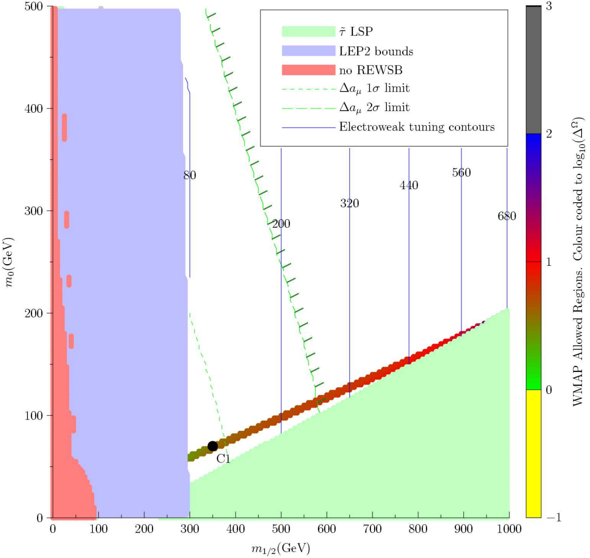
The CMSSM with $A_0 = 0$, $\tan\beta = 50$; S.F.King, J.P.R.: hep-ph/0609147,



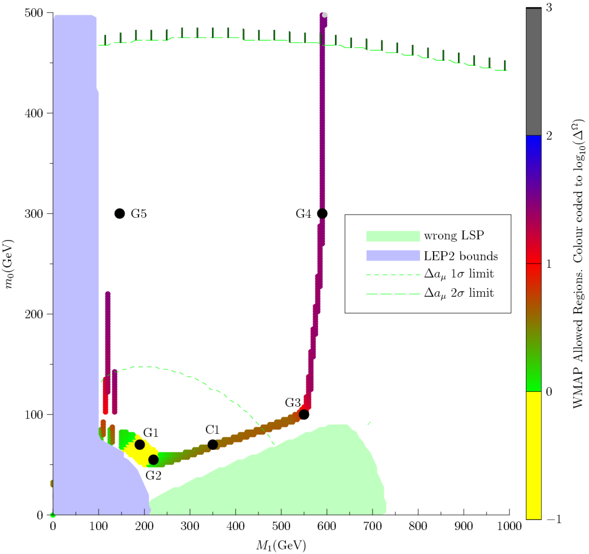
The CMSSM with $A_0 = 0$, $\tan\beta = 50$



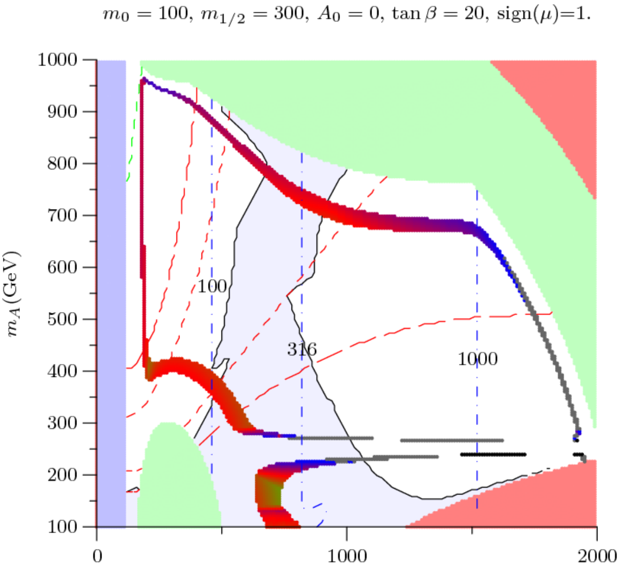
The CMSSM with $A_0 = 0,\ \tan\beta = 10$



Relaxing the CMSSM: non-universal gauginos



Non-Universal Higgs Masses; J. Ellis, S. F. King, JPR, in preparation



Naturalness in the full MSSM

By relaxing our constraints we can find typical tuning scales across different dark matter annihilation channels.

Naturalness in the full MSSM

By relaxing our constraints we can find typical tuning scales across different dark matter annihilation channels.

Region	Typical Δ^{Ω}
Mixed bino/wino	~ 30
Mixed bino/higgsino	$30 - 60$
Mixed bino/wino/higgsino	$4 - 60$
Bulk region (t-channel $\tilde{f}$ exchange)	< 1
slepton coannihilation (low M_1, m_0)	$3 - 15$
slepton coannihilation (large M_1, m_0, $\tan\beta$)	~ 50
sneutrino coannihilation	~ 100
Z-resonant annihilation	~ 10
h^0-resonant annihilation	$10 - 1000$
A^0-resonant annihilation	$80 - 300$

Naturalness in the full MSSM

By relaxing our constraints we can find typical tuning scales across different dark matter annihilation channels.

Region	Typical Δ^{Ω}
Mixed bino/wino	~ 30
Mixed bino/higgsino	$30 - 60$
Mixed bino/wino/higgsino	$4 - 60$
Bulk region (t-channel $\tilde{f}$ exchange)	< 1
slepton coannihilation (low M_1, m_0)	$3 - 15$
slepton coannihilation (large M_1, m_0, $\tan\beta$)	~ 50
sneutrino coannihilation	~ 100
Z-resonant annihilation	~ 10
h^0-resonant annihilation	$10 - 1000$
A^0-resonant annihilation	$80 - 300$

Therefore the MSSM allows for **natural dark matter**.

Going to the GUT scale

When dealing with the MSSM we have the inputs:

$$a_{MSSM} \in \{m_i, M_i, A_i, \tan\beta\}$$

Going to the GUT scale

When dealing with the MSSM we have the inputs:

$$a_{MSSM} \in \{m_i, M_i, A_i, \tan\beta\}$$

In some explicit model of SUSY breaking we will have a smaller set of parameters that determine the SUSY breaking masses e.g.:

$$a_{GUT}$$

Going to the GUT scale

When dealing with the MSSM we have the inputs:

$$a_{MSSM} \in \{m_i, M_i, A_i, \tan\beta\}$$

In some explicit model of SUSY breaking we will have a smaller set of parameters that determine the SUSY breaking masses e.g.:

$$a_{GUT}$$

The dark matter tuning with respect to a_{GUT}, $\Delta^{\Omega}_{a_{GUT}}$ is directly related to $\Delta^{\Omega}_{a_{MSSM}}$ via the relation:

$$\Delta^{\Omega}_{a_{GUT}} = \sum_{a_{MSSM}} \frac{a_{GUT}}{a_{MSSM}} \frac{\partial a_{MSSM}}{\partial a_{GUT}} \Delta^{\Omega}_{a_{MSSM}}$$

Going to the GUT scale

When dealing with the MSSM we have the inputs:

$$a_{MSSM} \in \{m_i, M_i, A_i, \tan\beta\}$$

In some explicit model of SUSY breaking we will have a smaller set of parameters that determine the SUSY breaking masses e.g.:

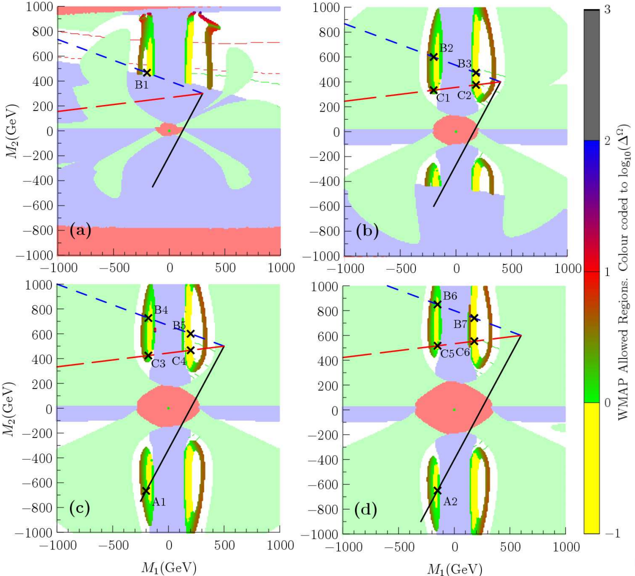
$$a_{GUT}$$

The dark matter tuning with respect to a_{GUT}, $\Delta^{\Omega}_{a_{GUT}}$ is directly related to $\Delta^{\Omega}_{a_{MSSM}}$ via the relation:

$$\Delta^{\Omega}_{a_{GUT}} = \sum_{a_{MSSM}} \frac{a_{GUT}}{a_{MSSM}} \frac{\partial a_{MSSM}}{\partial a_{GUT}} \Delta^{\Omega}_{a_{MSSM}}$$

If we minimise the coefficients, we minimise the dark matter tuning.

An $SU(5)$ GUT model; S.F.King, JPR, D.P.Roy: arXiv:0705.4219



Naturalness: Why should we care?

1. SUSY is directly motivated by naturalness considerations.

Naturalness: Why should we care?

1. SUSY is directly motivated by naturalness considerations.
    - The hierarchy problem is an extreme case of fine-tuning.

Naturalness: Why should we care?

1. SUSY is directly motivated by naturalness considerations.
    - The hierarchy problem is an extreme case of fine-tuning.
    - There are many claims for and against natural SUSY dark matter.

Naturalness: Why should we care?

1. SUSY is directly motivated by naturalness considerations.
   - The hierarchy problem is an extreme case of fine-tuning.
   - There are many claims for and against natural SUSY dark matter.
   - Theorists need to know the fine-tuning price of their pet model.

Naturalness: Why should we care?

1. SUSY is directly motivated by naturalness considerations.
   - The hierarchy problem is an extreme case of fine-tuning.
   - There are many claims for and against natural SUSY dark matter.
   - Theorists need to know the fine-tuning price of their pet model.
2. If the LHC lands us in a tuned region of the parameter space we can look for GUT models that mitigate this tuning.

Naturalness: Why should we care?

1. SUSY is directly motivated by naturalness considerations.
   - The hierarchy problem is an extreme case of fine-tuning.
   - There are many claims for and against natural SUSY dark matter.
   - Theorists need to know the fine-tuning price of their pet model.
2. If the LHC lands us in a tuned region of the parameter space we can look for GUT models that mitigate this tuning.
   - So (in a sense) fine-tuned regions are **"better"**.

Naturalness: Why should we care?

1. SUSY is directly motivated by naturalness considerations.
   - The hierarchy problem is an extreme case of fine-tuning.
   - There are many claims for and against natural SUSY dark matter.
   - Theorists need to know the fine-tuning price of their pet model.
2. If the LHC lands us in a tuned region of the parameter space we can look for GUT models that mitigate this tuning.
   - So (in a sense) fine-tuned regions are **"better"**.
3. The same measures of sensitivity can be used to relate LHC data directly to $\Omega_{CDM}h^2$.

Naturalness: Why should we care?

1. SUSY is directly motivated by naturalness considerations.
   - The hierarchy problem is an extreme case of fine-tuning.
   - There are many claims for and against natural SUSY dark matter.
   - Theorists need to know the fine-tuning price of their pet model.
2. If the LHC lands us in a tuned region of the parameter space we can look for GUT models that mitigate this tuning.
   - So (in a sense) fine-tuned regions are **"better"**.
3. The same measures of sensitivity can be used to relate LHC data directly to $\Omega_{CDM}h^2$.
   - By studying sensitivity to EW SUSY parameters we can find the sensitivity needed at the LHC to **disprove the MSSM** (with certain priors).