Compressed supersymmetry and natural neutralino dark matter from annihilation to top quarks

PHENO 2007

May 7, 2007

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Based on: `hep-ph/0703097`

Executive Summary

Experimental results from LEP2, Tevatron, and WMAP put tension on the parameter space of minimal supersymmetry.

A possible resolution:

- “Compressed” supersymmetry: the spectrum of superpartner masses has a narrower range than is found in the most popular models.
- Dark matter with observed density explained by neutralino LSP pair annihilation to top quark-antiquark pairs.

This scenario has sharp implications for collider physics.

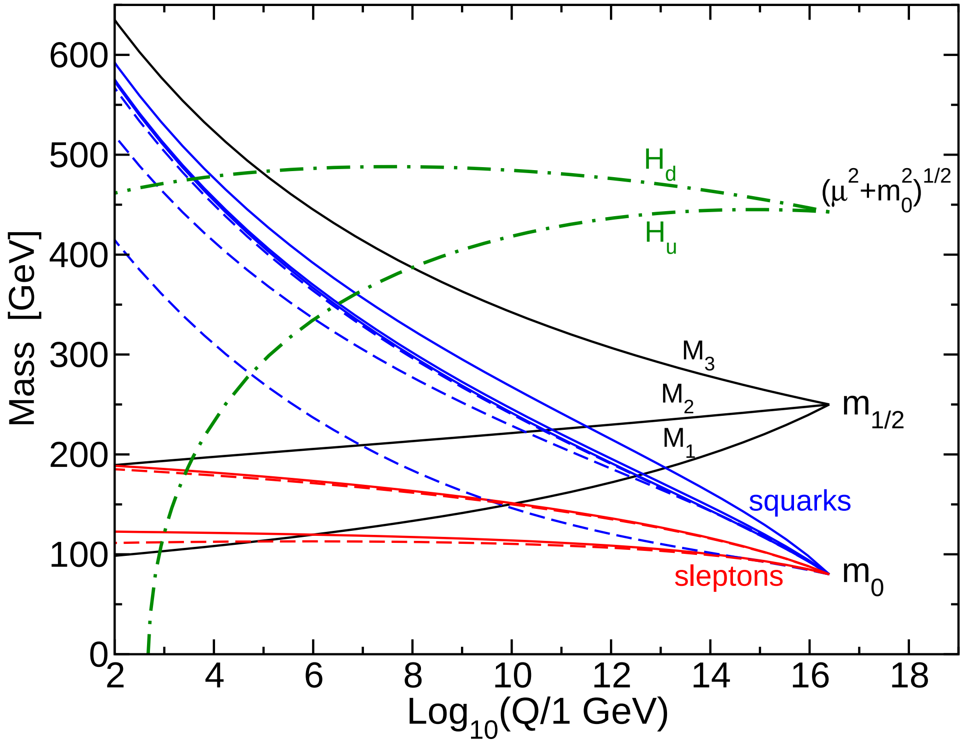
A condition for Electroweak Symmetry Breaking is:

$$m_Z^2 \;=\; 2\left(|m_{H_u}^2| - |\mu|^2\right) + \text{small loop corrections } + \mathcal{O}(1/\tan^2\beta).$$

Here $|\mu|^2$ is a SUSY-preserving Higgs squared mass,
$m_{H_u}^2$ is a SUSY-violating Higgs scalar squared mass.

Cancellation in minimal mSUGRA models is typically at the percent level.

Assuming unified gaugino and scalar masses near the GUT scale predicts a hierarchical mass spectrum at the TeV scale:



The large magnitude and slope of $-m_{H_u}^2$ is mostly the gluino's fault.

Fine tuning of the electroweak scale is reduced if the pernicious influence of the gluino is suppressed.

(G. Kane and S. King, `hep-ph/9810374`)

$$\begin{aligned} -m_{H_u}^2 &= 1.92\hat{M}_3^2 + 0.16\hat{M}_2\hat{M}_3 - 0.21\hat{M}_2^2 - 0.33\hat{M}_3\hat{A}_t \\ &\quad -0.63\hat{m}_{H_u}^2 + 0.36\hat{m}_{t_L}^2 + 0.28\hat{m}_{t_R}^2 \\ &\quad + \text{many terms with tiny coefficients} \end{aligned}$$

The hatted parameters on the right are at the GUT scale, result is at the TeV scale.

If one takes a smaller gluino mass at the GUT scale, say $\hat{M}_3/\hat{M}_2 \sim 1/3$, then $-m_{H_u}^2$ will be much smaller.

As a result, $|\mu|^2$ will be smaller also.

Are there reasonable models in which $\hat{M}_3/\hat{M}_2$ is smaller?

Answer: yes, many.

I'll review one mechanism, which works even if there is really a GUT theory like $SU(5)$ or $SO(10)$.

But results below about dark matter don't depend crucially on this choice.

The F-term VEV that breaks SUSY could transform as anything in the symmetric product of the adjoint rep with itself.

For $SU(5)$, the F term could be in:

$$(\mathbf{24} \times \mathbf{24})_S = \mathbf{1} + \mathbf{24} + \mathbf{75} + \mathbf{200}.$$

The bino, wino, and gluino masses can be parameterized by:

$$\begin{aligned}
\hat{M}_1 &= m_{1/2}(1 + C_{24} + 5C_{75} + 10C_{200}), \\
\hat{M}_2 &= m_{1/2}(1 + 3C_{24} - 3C_{75} + 2C_{200}), \\
\hat{M}_3 &= m_{1/2}(1 - 2C_{24} - C_{75} + C_{200}).
\end{aligned}$$

The special case $C_{24} = C_{75} = C_{200} = 0$ recovers the mSUGRA model.

To obtain $\hat{M}_3/\hat{M}_2 \sim 1/3$, one needs only $C_{24} \sim 0.2$.

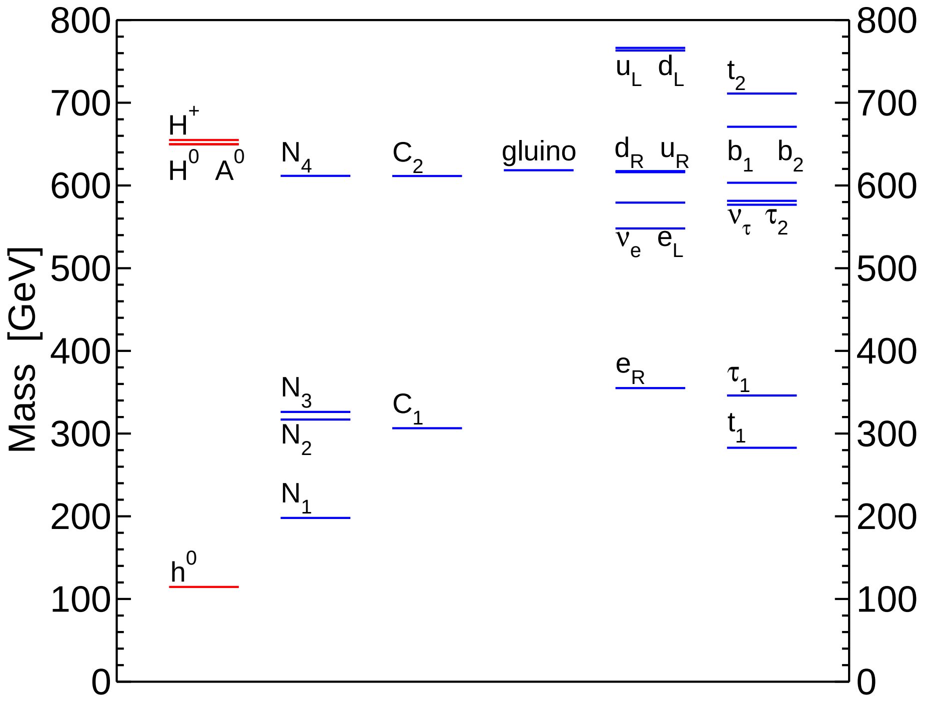
In the following, I will assume that $\hat{M}_3/\hat{M}_2$ is indeed comparable to $1/3$ at the apparent GUT scale.

I will also assume (merely for simplicity and convenience) a common scalar squared mass m_0^2, and a unified, sizable and negative (scalar)^3 coupling A_0.

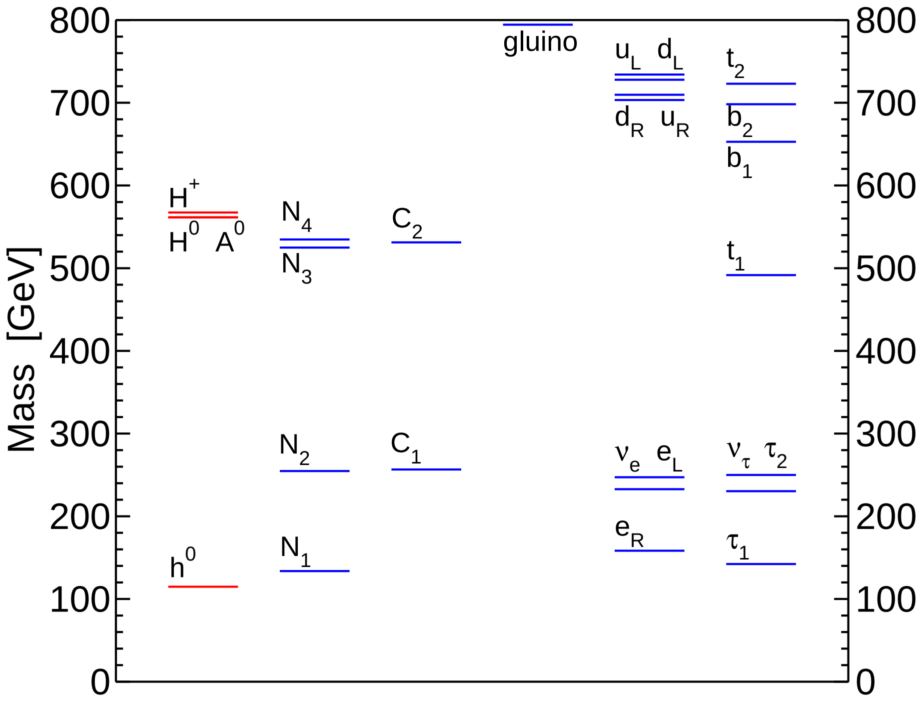
The result is a “compressed” SUSY spectrum, with a smaller ratio of the masses of the heaviest SUSY particle and the LSP.

Comparison of Compressed SUSY and mSUGRA, for models with $\Omega_{\rm DM} h^2 = 0.11$, Higgs mass m_h just above LEP2 bound, and heaviest squarks in the 700-800 GeV range:

Compressed SUSY $\hat{M}_3/\hat{M}_2 = 1/3$



mSUGRA $\hat{M}_3/\hat{M}_2 = 1$



Note $|\mu|^2$ lower in Compressed SUSY; less cancellation needed.

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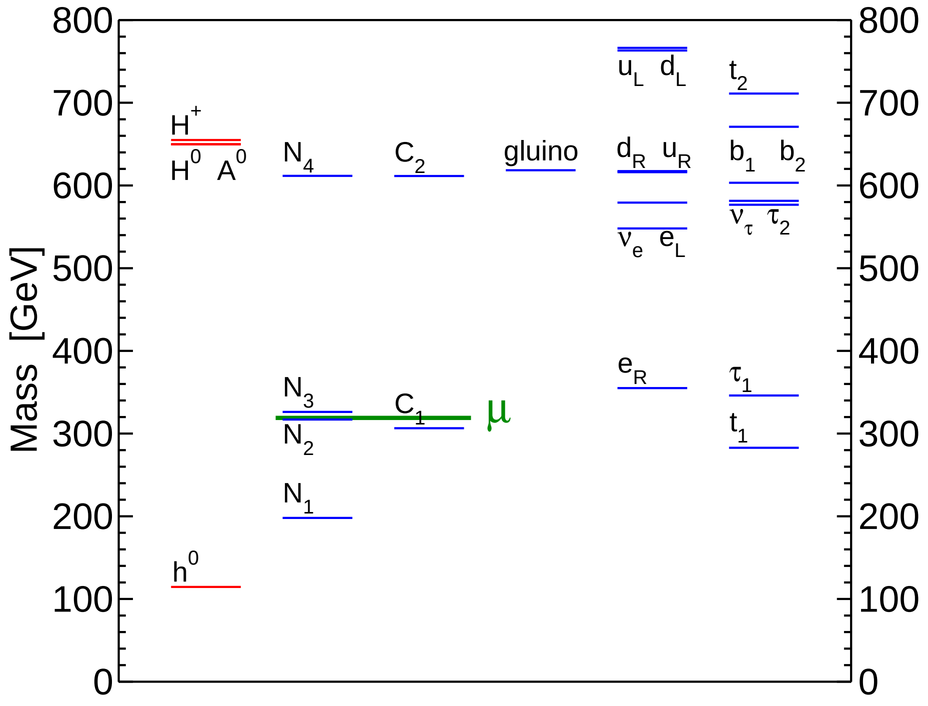
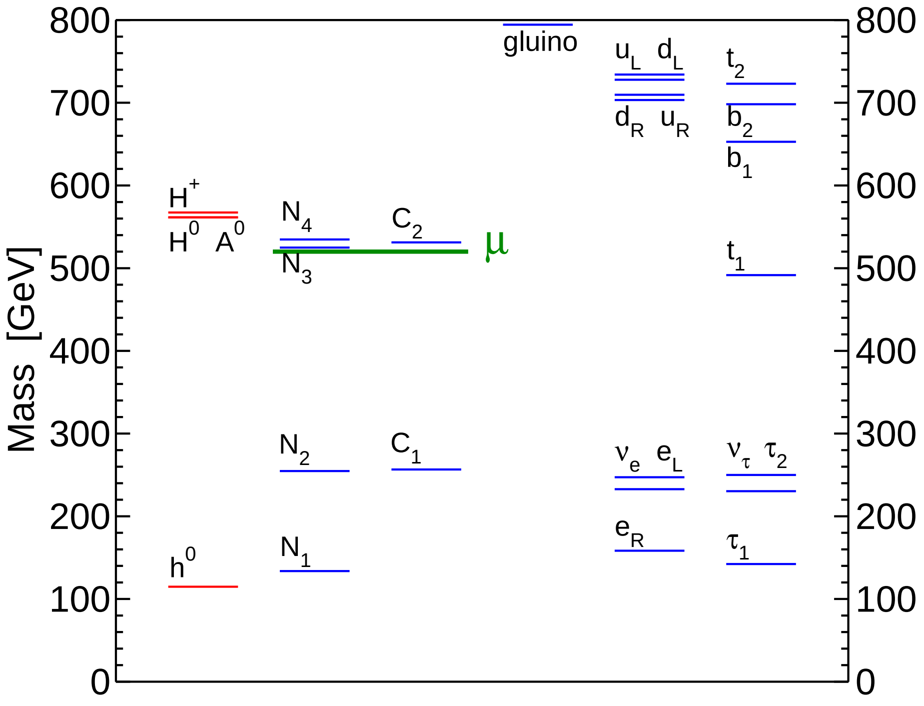


mSUGRA $\hat{M}_3/\hat{M}_2 = 1$



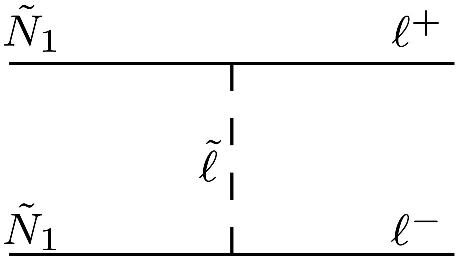
Note $|\mu|^2$ lower in Compressed SUSY; less cancellation needed.

WMAP and other experiments have measured $\Omega_{\rm DM} h^2 \approx 0.11$

In much of the remaining SUSY parameter space, $\Omega_{\rm DM} h^2$ comes out too large. A mechanism for efficient annihilation of LSPs in the early universe is needed.

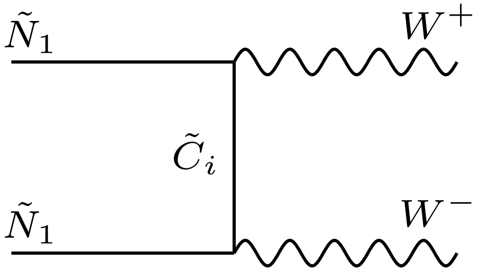
Four main scenarios within the MSSM have been proposed:

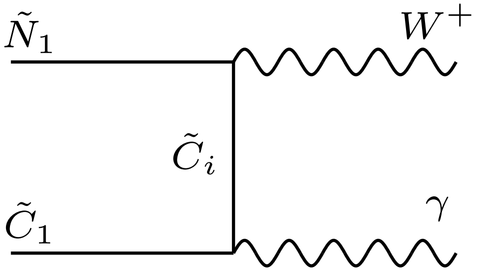
1) "Bulk region": LSPs annihilate through slepton exchange.

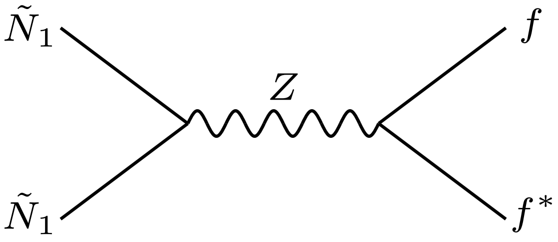


In mSUGRA, it is tough to accomodate this and LEP2 bounds at the same time.

2) “Focus point/Small μ”: LSPs have enough higgsino content to annihilate or coannihilate to/through weak bosons

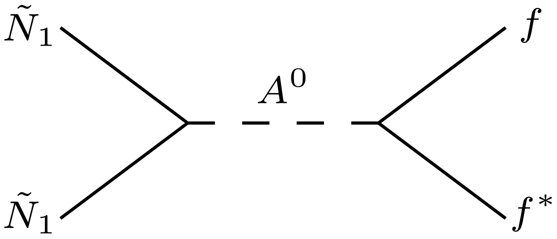






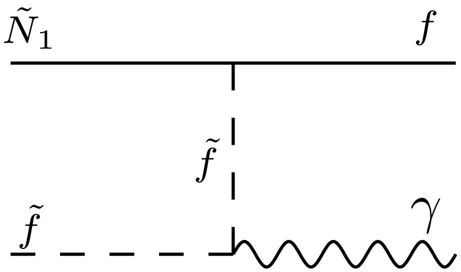
Need to get μ just right.

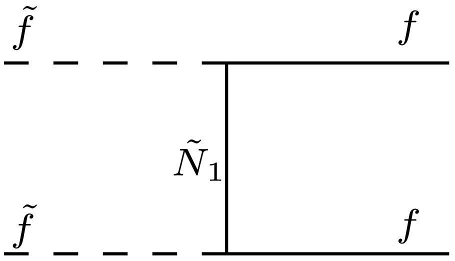
3) “Higgs resonance (funnel)”: LSPs annihilate by s channel pseudoscalar Higgs exchange



Need LSP mass to be close to $m_{A^0}/2$, usually large $\tan\beta$.

4) “Co-annihilation region”: LSPs co-annihilate with sleptons (or top squarks) in thermal equilibrium



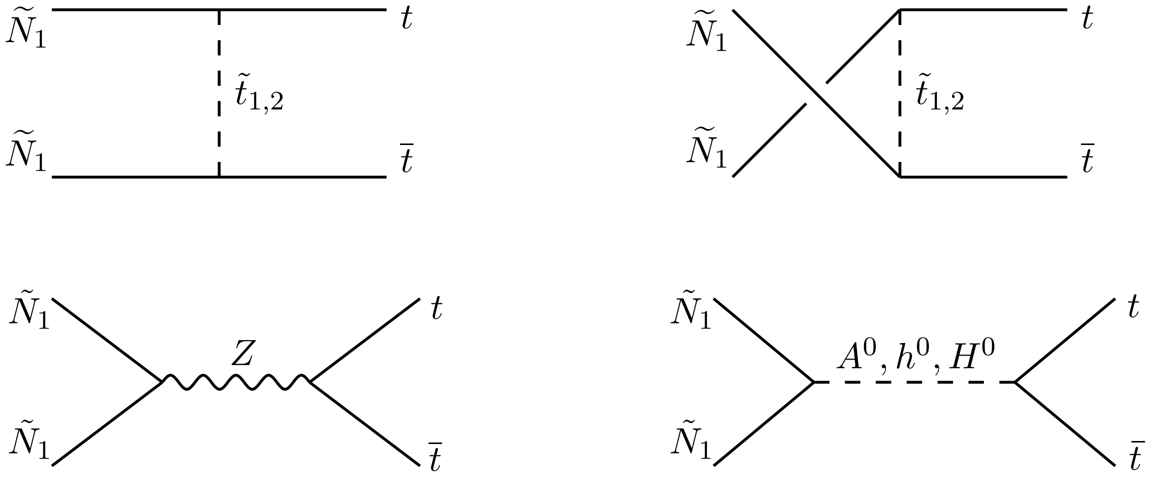


Need a small sfermion-LSP mass difference, tuned just right.

In Compressed Supersymmetry, I claim another scenario becomes natural, because the LSP is naturally heavier than the top quark, and the top squark is the next-lightest superpartner. . .

An alternative: Pair annihilation of LSPs to top quarks, mediated by top squark exchange.

Diagrams leading to $\tilde{N}_1 \tilde{N}_1 \to t\bar{t}$:



To get $\Omega_{\rm DM} h^2$ into the WMAP allowed range, need roughly:

$$\begin{aligned} m_t \; < \; m_{\tilde{N}_1} \;\; &\lesssim \;\; m_t + 100 \,\mathrm{GeV}, \\ m_{\tilde{N}_1} + 25 \,\mathrm{GeV} \;\; \lesssim \;\; m_{\tilde{t}_1} \;\; &\lesssim \;\; m_{\tilde{N}_1} + 100 \,\mathrm{GeV}. \end{aligned}$$

In Compressed Supersymmetry, the $\tilde{t}_1$ exchange can naturally dominate.

(The Z exchange diagram interferes destructively.)

In the following, I consider models with m_0 and $\hat{M}_1$ variable, with

$$\begin{aligned}
&1.5\hat{M}_1 = \hat{M}_2 = 3\hat{M}_3, \\
&\tan\beta = 10 \\
&\mu > 0.
\end{aligned}$$

Imposed Higgs mass constraint (noting significant theoretical uncertainties):

$$M_h > 113\,\mathrm{GeV}.$$

Also, I assume

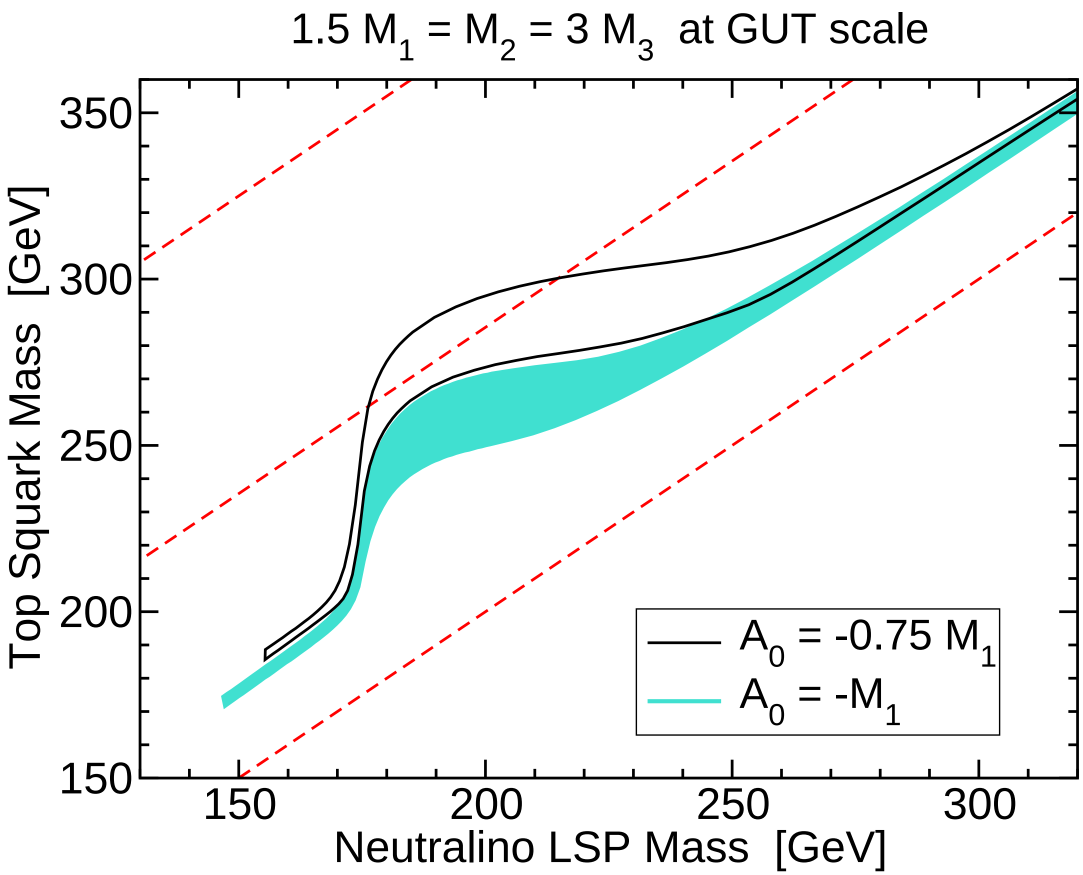
$$M_t = 175\,\mathrm{GeV}$$

which is somewhat optimistic compared to the current central value.

Finally, I impose the rather conservative constraint on dark matter:

$$0.09 < \Omega_{\mathrm{DM}} h^2 < 0.13$$

Allowed regions in the $m_{\tilde{t}_1}, m_{\tilde{N}_1}$ plane:



In the upward bulge regions, $\tilde{N}_1\tilde{N}_1 \rightarrow t\bar{t}$ is mediated mostly by $\tilde{t}_1$ exchange.

Below upper dashed line, $\tilde{t}_1 \rightarrow t\tilde{N}_1$ is forbidden.

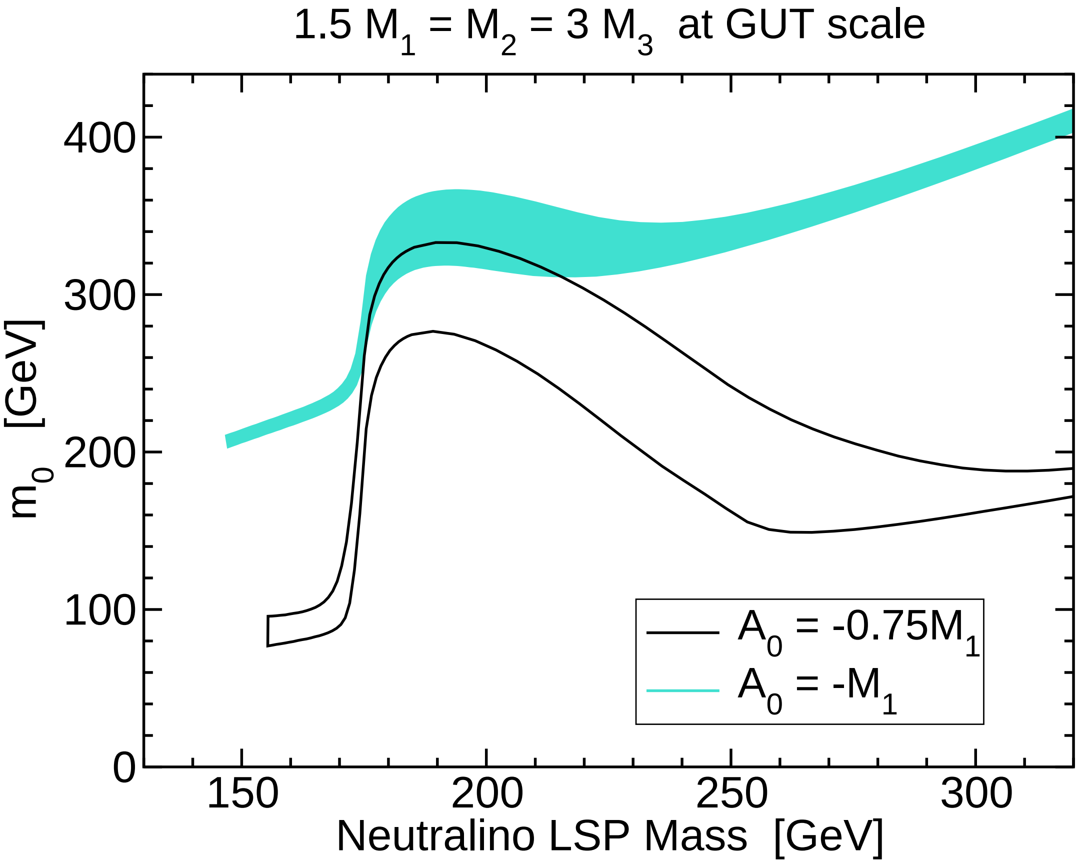
Below middle dashed line, $\tilde{t}_1 \rightarrow Wb\tilde{N}_1$ is also forbidden.

Below lowest dashed line, $\tilde{t}_1$ is LSP.

Regions are cut off on the left by the M_h constraint.

Thin regions on either side of the bulge obtain correct dark matter density by co-annihilation with top-squark .

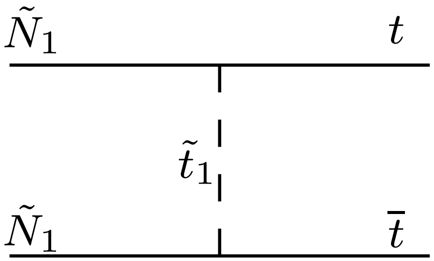
Common GUT-scale scalar mass m_0 for the same models:



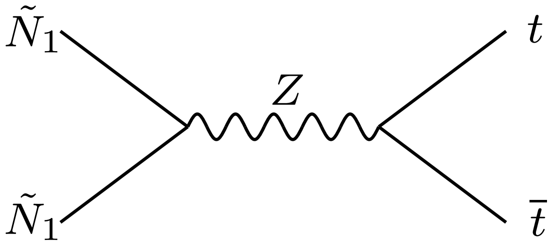
In these models, **all** soft SUSY-breaking mass parameters are less than $\hat{M}_1$, $\hat{M}_2$.

Beating the LEP Higgs constraint (almost) forces $m_{\tilde{N}_1}$ to be larger than m_t.

Unlike other SM quark and lepton final states, $t\bar{t}$ does not have p-wave suppression.



(+ u-channel)



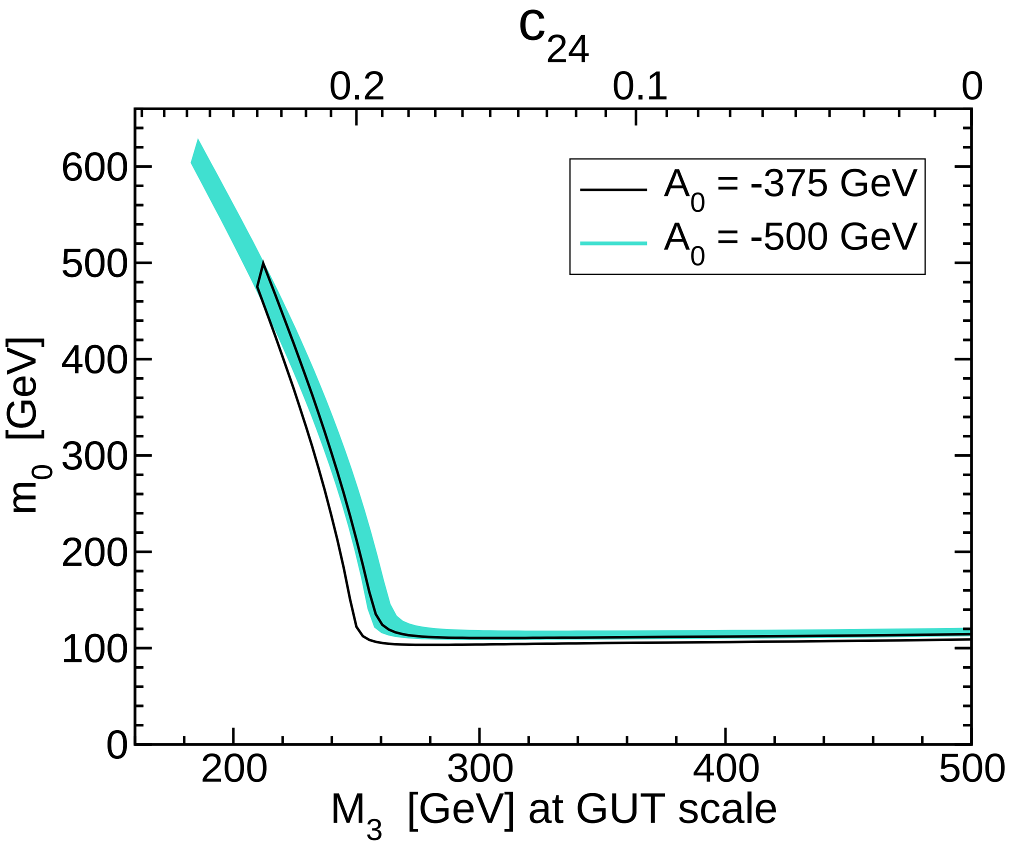
In most of the WMAP allowed region, the Z exchange diagram gives substantial destructive interference. The ratio of contributions to the initial state ${}^{2s+1}L_J = {}^1S_0$ amplitude is:

$$A_Z/A_{\tilde{t}_1} \approx -0.3$$

and other amplitudes are relatively minor.

Another slice through parameter space:

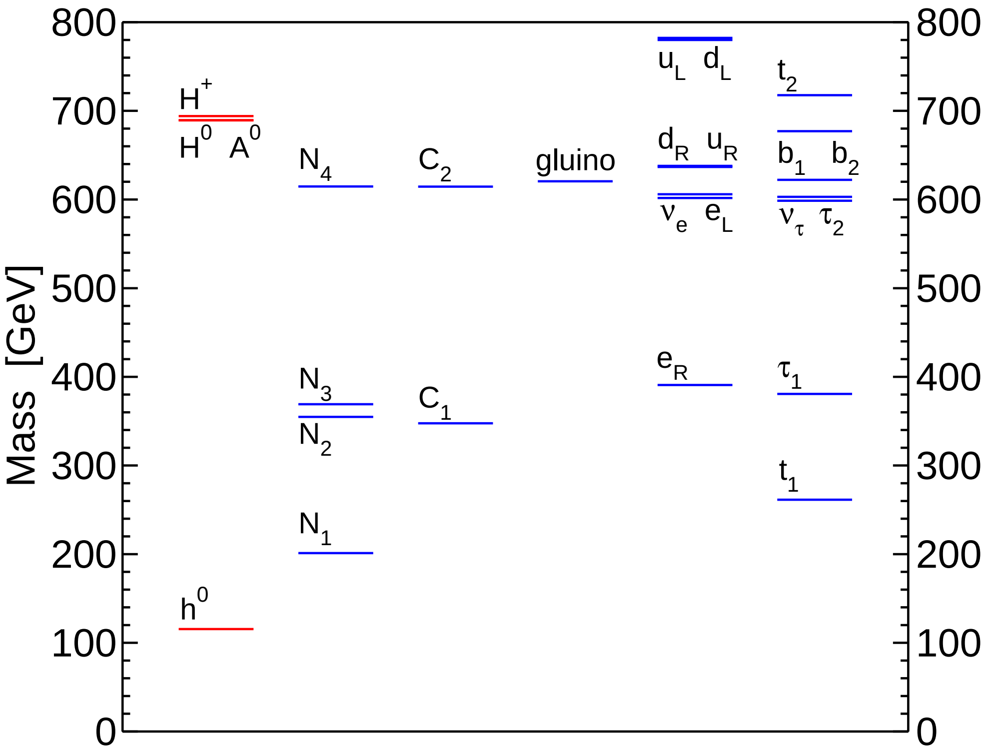
Hold $\hat{M}_1 = 500$ GeV fixed (so that $m_{\tilde{N}_1} \approx 200$ GeV). Then vary the gaugino non-universality parameter C_{24}, and m_0.



Thin horizontal strips on right are stau co-annihilation regions.

Thicker sloping regions on left are where $\tilde{N}_1 \tilde{N}_1 \rightarrow t\bar{t}$ dominates through $\tilde{t}_1$.

This scenario for SUSY dark matter has distinctive implications for colliders.



Important decays for

hadron colliders:

$$\tilde{t}_1 \to c\tilde{N}_1 \qquad (100\%)$$

$$\tilde{g} \to \begin{cases} t\,\tilde{t}_1^* & (\sim 50\%) \\ \bar{t}\,\tilde{t}_1 & (\sim 50\%) \end{cases}$$

$$\tilde{q}_L \to \begin{cases} q\tilde{g} & (\sim 78\%) \\ q'\tilde{C}_2 & (\sim 11\%) \end{cases}$$

$$\tilde{q}_R \to q\tilde{N}_1 \qquad (\sim 90\%)$$

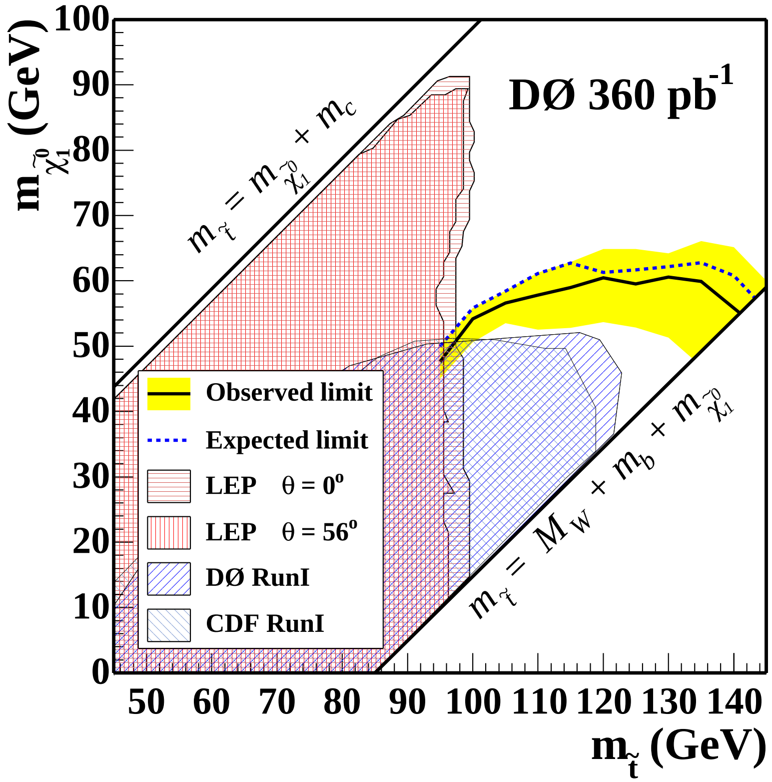
More generally, $\tilde{t}_1$ cannot decay to $t\tilde{N}_1$ in this scenario.

The spectrum is relatively heavy; the compression is upwards to make M_h heavy, so weakly-interacting superpartners are hard to see at hadron colliders.

The target is here!

In this scenario, superpartners are too heavy to give much hope at the Tevatron. One can look for the top squark $\tilde{t}_1$ by:

$$p\bar{p} \longrightarrow \tilde{t}_1\tilde{t}_1^* \longrightarrow c\bar{c}\tilde{N}_1\tilde{N}_1 \longrightarrow c\,\bar{c} + \not{\!\!E}_T$$



Usual Tevatron signals for SUSY, trileptons, like-sign dileptons, jets + $\not{\!\!E}_T$, all seem to be very hard or impossible. Not enough events.

LHC discovery signal

If $\tilde{t}_1 \to c\tilde{N}_1$, gluino pair production leads to:

$$pp \to \tilde{g}\tilde{g} \to \begin{cases} t\,\bar{t}\,\tilde{t}_1\,\tilde{t}_1^* \to t\,\bar{t}\,c\,\bar{c} + \not{E}_T & (50\%) \\ t\,t\,\tilde{t}_1^*\,\tilde{t}_1^* \to t\,t\,\bar{c}\,\bar{c} + \not{E}_T & (25\%) \\ \bar{t}\,\bar{t}\,\tilde{t}_1\,\tilde{t}_1 \to \bar{t}\,\bar{t}\,c\,c + \not{E}_T & (25\%) \end{cases}$$

Kraml and Raklev (2005) used like-charge leptonic decay modes for both top quarks. Both discovery and mass measurements are possible up to a gluino mass of about 900 GeV.

Most SUSY events at LHC will go through the gluino. (So add softer, light-flavor, jets from squark decays.)

An unfortunate feature of Compressed Supersymmetry: sleptons decouple almost perfectly from the LHC.

They are too heavy to be found directly by Drell-Yan or Vector Boson Fusion, and do not appear in the cascade decay chains of squarks or gluinos in significant numbers.

After LHC, we may have discovered the gluino and many squarks, but not be able to say <u>anything</u> about the sleptons.

Charginos and neutralinos may be almost as bad.

The heavier, wino-like chargino $\tilde{C}_2$ can appear in the decays of left-handed squarks with $\sim 10\%$ branching fraction.

Then it decays to (in the example model shown earlier):

$$\tilde{C}_2 \to \begin{cases} \tilde{N}_3 W & (\sim 26\%) \\ \tilde{N}_2 W & (\sim 26\%) \\ \tilde{C}_1 Z & (\sim 25\%) \\ \tilde{C}_1 h & (\sim 22\%) \end{cases}$$

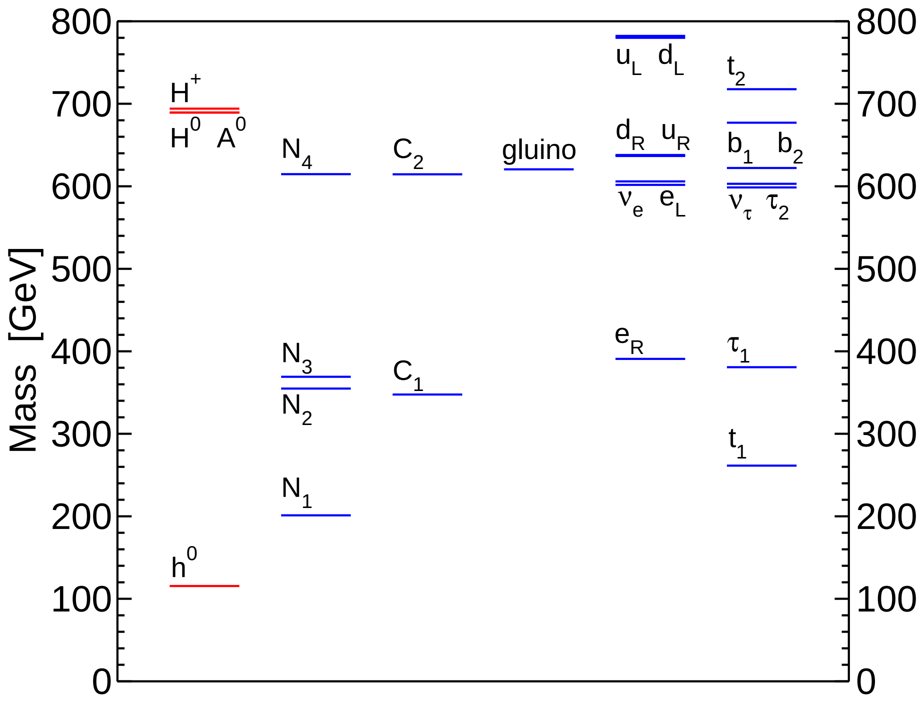
$$\tilde{N}_2 \to \begin{cases} \tilde{N}_1 h & (\sim 90\%) \\ \tilde{N}_1 Z & (\sim 10\%) \end{cases}$$

$$\tilde{N}_3 \to \tilde{N}_1 Z \qquad (\sim 97\%)$$

$$\tilde{C}_1 \to \tilde{t}_1 b \qquad (\sim 95\%)$$

Leptonic branchings are small; final states are varied. Good Luck sorting this out!

A typical feature of Compressed SUSY with $\tilde{N}_1\tilde{N}_1 \to t\bar{t}$ dark matter: no visible superpartners at a $\sqrt{s} = 500$ GeV Linear Collider!



Only a light Higgs h^0 (nearly indistinguishable from Standard Model) will be directly visible. Also possible, initial state radiation:

$$e^+e^- \to \tilde{N}_1\tilde{N}_1\gamma$$

Outlook

- Non-universal gaugino masses at the GUT scale with $\hat{M}_3/\hat{M}_2 \lesssim 1/3$ alleviate the fine-tuning problem of minimal SUSY, leading to a compressed mass spectrum
- A distinctive scenario for dark matter: $\tilde{N}_1\tilde{N}_1 \to t\bar{t}$ through $\tilde{t}_1$ exchange dominates
- Discovery is impossible at the past LEP2 collider, likely at the imminent LHC (but some sleptons decouple, and Higgsinos and Winos will be tough)
- In this scenario, a higher beam energy for a future ILC may be preferable. We'll know better after the LHC.
- Studies of direct and indirect dark matter detection prospects specific to this scenario are in progress.