# Expectations for supersymmetry after the LHC

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A Popular Folk Theorem:

**If supersymmetry is correct, and responsible for the stablization of the electroweak scale, then the LHC will discover it.**

The hierarchy of the Planck scale to the weak scale can only be explained by supersymmetry if superpartners are light enough to be produced in $pp$ collisions at $\sqrt{s} \approx 14$ TeV.

I fully subscribe to this belief, despite the inherent fuzziness of arguments based on fine-tuning.

**But, what questions are likely to remain unanswered by LHC? What will it take to answer them?**

Supersymmetry is a symmetry between fermions and bosons that predicts ratios of certain couplings.

To say that we understand and have verified supersymmetry with scientific certainty requires that we find *all* of the superpartners and at least produce evidence for the predicted spins and couplings.

Unfortunately, this is not likely to occur at LHC.

## The High-Hanging Fruit

Superpartners can effectively decouple from the LHC if they

- have small direct production cross-sections (only electroweak interactions and heavier than a few hundred GeV), and
- are not produced indirectly in great numbers by decays of heavier superpartners

Heavy Higgsino-like charginos and neutralinos are a common example of this.

Sleptons can also very easily decouple, if heavier than the gaugino-like neutralinos and charginos.

Even gaugino-like neutralinos and charginos might effectively decouple from LHC, and even in motivated models.

## Higgsinos: the Forgotten Superpartners

Higgsinos are the supersymmetric partners of the Higgs bosons, and consist of a charge $\pm 1$ Dirac fermion (one of the two charginos) and two charge 0 Majorana fermions (two of the four neutralinos).

If gauginos are lighter, then

$$\begin{aligned} \widetilde{H}^{\pm} &\approx \widetilde{C}_2, \\ \widetilde{H}^0,\ \widetilde{H}^{0\prime} &\approx \widetilde{N}_3,\ \widetilde{N}_4. \end{aligned}$$

(But this is not always the case.)

Example: in the infamous SPS1a$'$ benchmark model:

$$m_{\widetilde{C}_2^\pm} \sim m_{\widetilde{N}_3} \sim m_{\widetilde{N}_4} \approx 410 \text{ GeV}$$

are Higgsino-like, with very small production rates.

The largest branching ratio for anything else into $\widetilde{C}_2$, $\widetilde{N}_3$, or $\widetilde{N}_4$ is:

$$\text{BR}(\widetilde{t}_2 \longrightarrow b\widetilde{C}_2) = 15\%,$$

which is swamped by $\widetilde{t}_2 \longrightarrow b\widetilde{C}_1$.

Everything else is at the $\sim 1\%$ level.

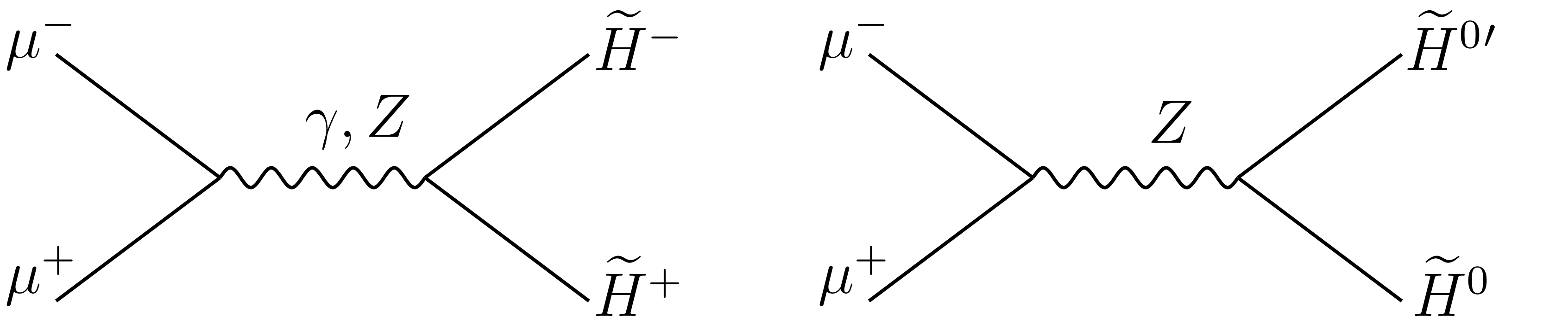
The fraction of all SUSY events with Higgsinos in them is tiny, and they have no good distinguishing features. They will be lost in huge SUSY backgrounds. (Prove me wrong!)

Maybe these Higgsino-like fermions can be found at an ILC with $\sqrt{s} \sim$ 800 GeV.

But, how will we know in advance? Having decoupled from the LHC, their masses will be still unknown to us.

At a high-energy lepton collider, Higgsinos can be produced by:

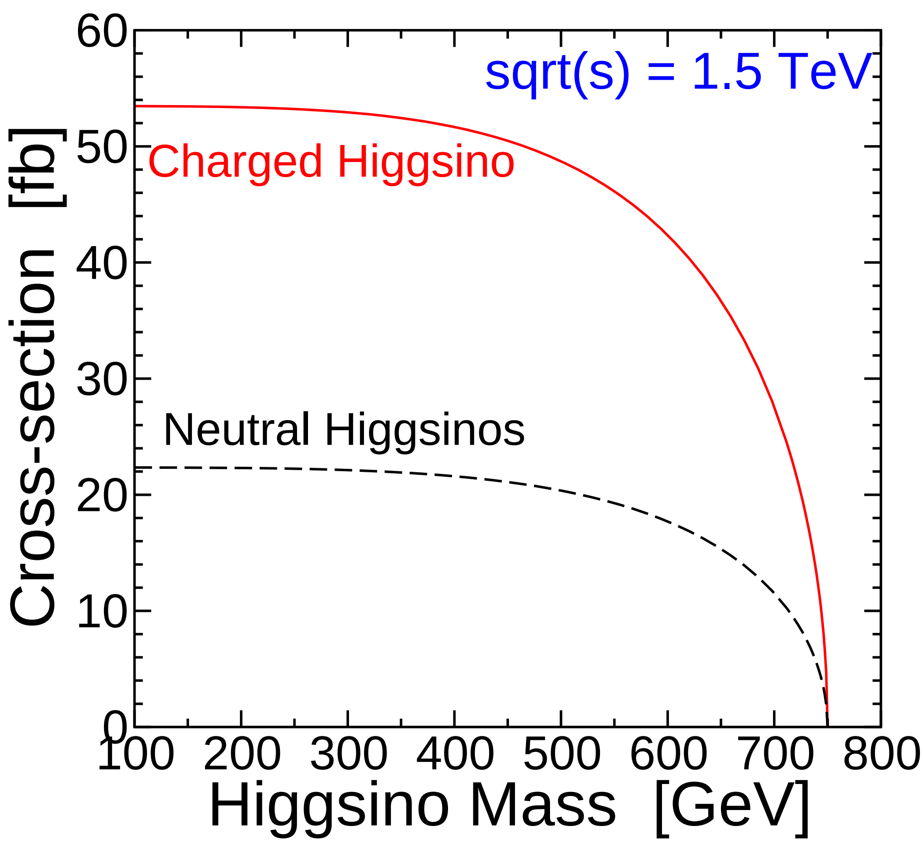
$$\mu^-\mu^+ \;\rightarrow\; \gamma^*, Z^* \;\rightarrow\; \widetilde{H}^+\widetilde{H}^-$$
$$\mu^-\mu^+ \;\rightarrow\; Z^* \;\rightarrow\; \widetilde{H}^0\widetilde{H}^{0\prime}$$

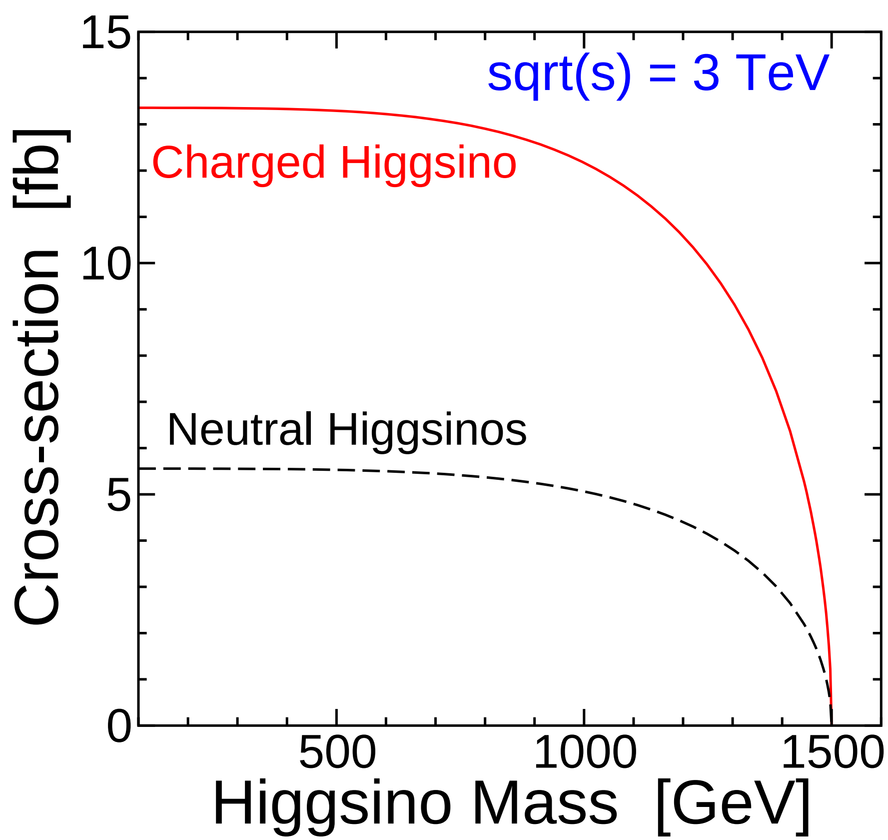



(Note: $Z$ does not couple to $\widetilde{H}^0\widetilde{H}^0$ or to $\widetilde{H}^{0\prime}\widetilde{H}^{0\prime}$ in the pure Higgsino limit.)

In the pure Higgsino limit, the cross-sections only depend on the masses.

Cross-sections for Higgsino-like charginos and neutralinos in $\mu^-\mu^+$ collisions:




Recall $10^{34}$ cm$^{-2}$ s$^{-1}$ $\longrightarrow$ $\sim$ 100 fb$^{-1}$/year.

After making Higgsinos at a muon collider, how do they decay?

For the SPS1a$'$ model, prominent Higgsino decay modes are:

$$\widetilde{C}_2 \to \begin{cases} W\widetilde{N}_2 & (25\%) \\ Z\widetilde{C}_1 & (22\%) \\ h^0\widetilde{C}_1 & (18\%) \\ b\widetilde{t}_1 & (10\%) \end{cases}$$

$$\widetilde{N}_3 \to \begin{cases} W^+\widetilde{C}_1^- & (30\%) \\ W^-\widetilde{C}_1^+ & (30\%) \\ Z\widetilde{N}_2 & (22\%) \end{cases} \qquad \widetilde{N}_4 \to \begin{cases} W^+\widetilde{C}_1^- & (26\%) \\ W^-\widetilde{C}_1^+ & (26\%) \\ h^0\widetilde{N}_2 & (16\%) \\ h^0\widetilde{N}_1 & (7\%) \end{cases}$$

The final states can be somewhat complicated.

These are model-dependent, so a survey of possibilities and their prospects should be performed. (Has this already been done?)

An important clue to the form of SUSY at the weak scale is the Little Hierarchy Problem.

The LEP constraint $m_{h^0} \geq 114$ GeV seems to require heavy superpartners to contribute in loops to the Higgs boson mass.

This seems to imply a percent-level fine-tuning in the parameters, since the condition for Electroweak Symmetry Breaking is:

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

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

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`)

$$-m_{H_u}^2 = 1.92 M_3^2 + 0.16 M_2 M_3 - 0.21 M_2^2$$
$$+ \text{many terms with tiny coefficients}$$

The 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 $M_3/M_2 \sim 1/3$, then $-m_{H_u}^2$ will be much smaller.

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

Most experimental projections for SUSY at LHC and Tevatron are based on mSUGRA.

In mSUGRA, at the GUT scale $Q_U = 2 \times 10^{16}$ GeV, the gluino, wino, and bino mass parameters are assumed to be in the ratio

$$M_1 : M_2 : M_3 = 1 : 1 : 1$$

Relaxing this assumption leads to many interesting and qualitatively different collider signatures (too many to list here!)

More generally, one can parametrize:

$$
\begin{aligned}
M_1 &= m_{1/2}(1 + C_{24}), \\
M_2 &= m_{1/2}(1 + 3C_{24}), \\
M_3 &= m_{1/2}(1 - 2C_{24}).
\end{aligned}
$$

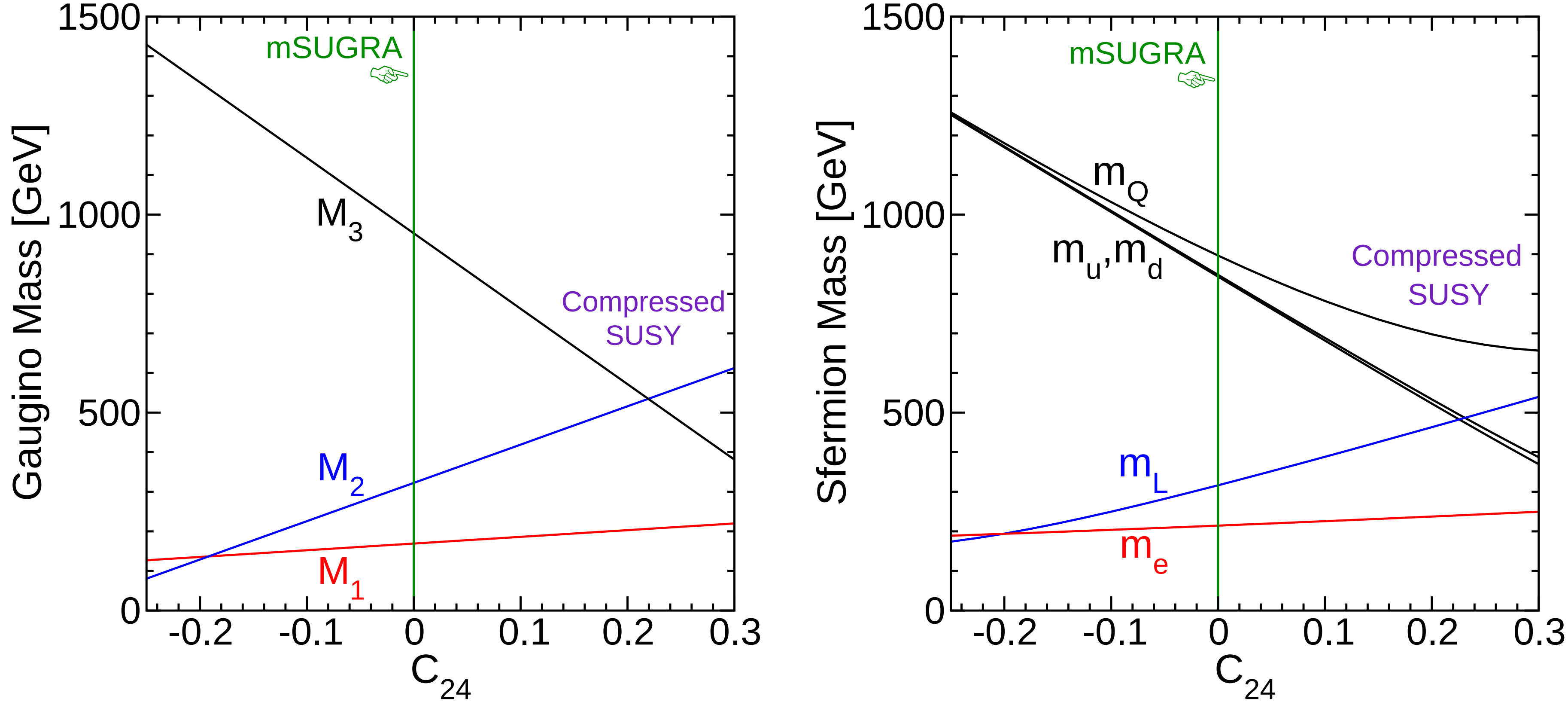
if the $F$ terms that break SUSY include both a singlet and a $\mathbf{24}$ of $SU(5)$ or a $\mathbf{54}$ of $SO(10)$.

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

In my opinion this deviation from universality is particularly compelling and worthy of study.

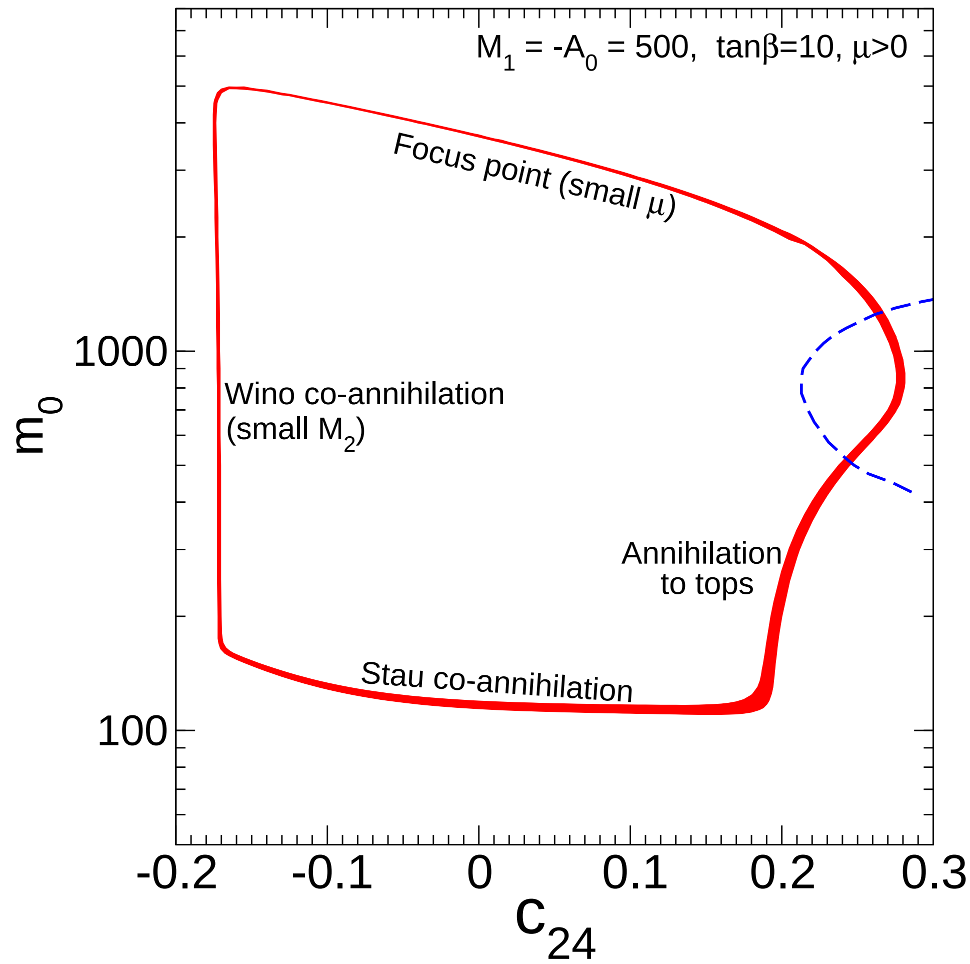
What are the effects of $C_{24}$ on the MSSM mass spectrum?

For $m_{1/2} = 500$ GeV, $m_0 = 150$ GeV, weak-scale parameters are:




"Compressed SUSY" arises for $C_{24} \gtrsim 0.15$. This ameliorates the little hierarchy problem, and allows for a unique mechanism for obtaining the correct thermal abundance of LSP dark matter.

In this enlarged parameter space, different dark matter allowed regions are continuously connected:

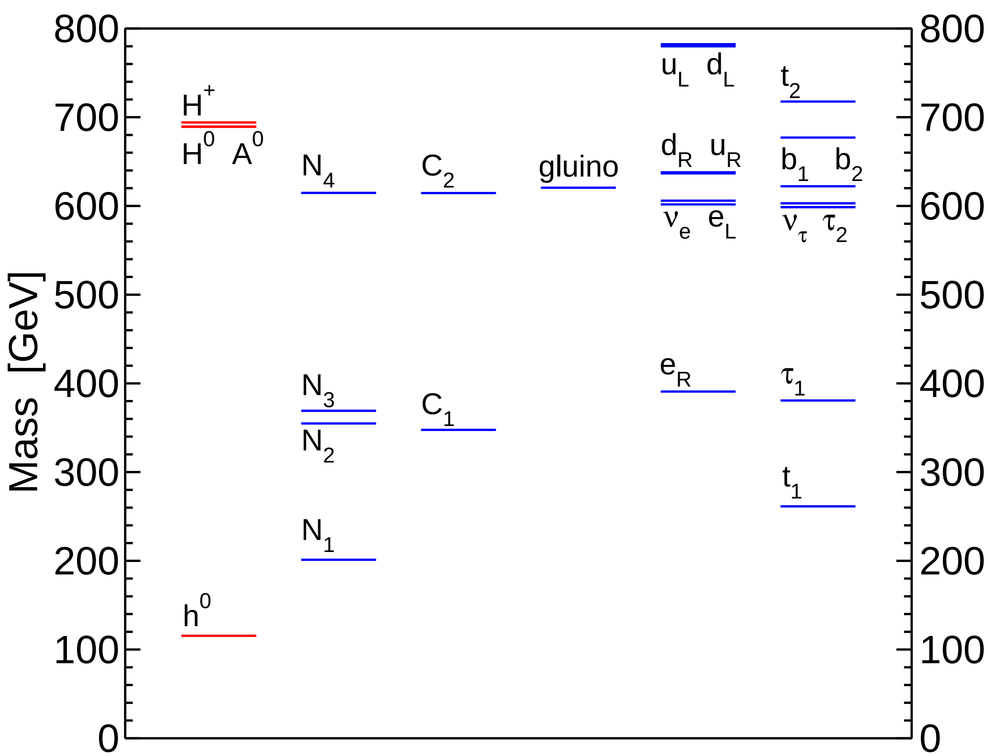



Red region is allowed by $\Omega_{\rm CDM} h^2 = 0.11 \pm 0.02$.

Points to the right of the dashed blue line have $M_h < 113$ GeV.

Too much dark matter inside the pentagon, too little outside.

A typical Compressed SUSY mass spectrum:




Important decays for hadron colliders:

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

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

$$\widetilde{q}_L \to \begin{cases} q\widetilde{g} & (\sim 80\%) \\ q'\widetilde{C}_2 & (\sim 10\%) \end{cases}$$

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

- Ratio of heaviest to lightest superpartner masses is $< 4$.
- Sleptons, charginos, and neutralinos other than LSP nearly decouple from LHC.
- A $\leq 1$ TeV linear collider will have limited reach, and we won't know what its reach is!

Note that these difficulties are directly related to the motivation provided by the Little Hierarchy Problem.

Reducing the fine-tuning of the MSSM suggests relatively large $M_2$, which enables the decoupling of sleptons and wino-like and higgsino-like chargino and neutralino masses from the LHC.

## Conclusion

- Decoupling of some (or even most) of the weakly-interacting superpartners from the LHC is a very common occurrence in SUSY parameter space.

- It is essential to learn about these particles in order to claim that we have understood SUSY!

- A prejudiced view of the MSSM suggests that the issue is worse than in popular benchmark models.

- A high-energy lepton collider can see the superpartners that decouple from the LHC, and will be indespensible to solving the problem.

- How high an energy will be needed? We don’t know yet.