Exploring Compressed Supersymmetry at the LHC

Stephen P. Martin

Northern Illinois University

Anticipating Physics at the LHC Conference

KITP, Santa Barbara, June 6, 2008

Outline:

- Motivation
- What is Compressed SUSY?
- Same-Sign tops signal
- Endpoints from gluino decays
- Stoponium!?
- Conclusion

In the MSSM, the condition for Electroweak Symmetry Breaking is:

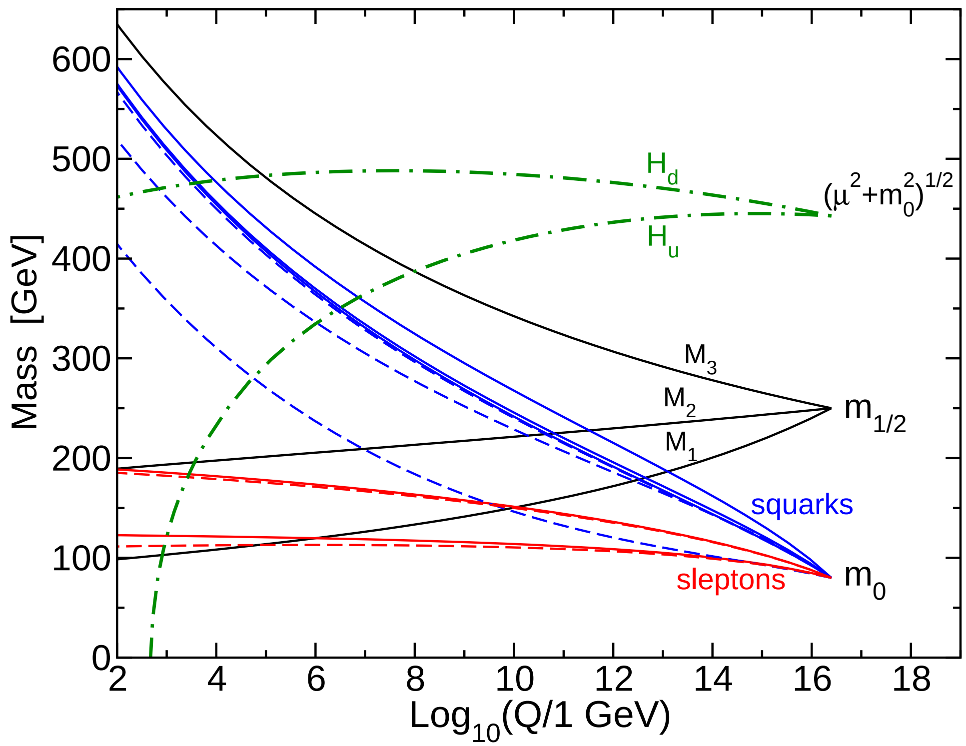
$$m_Z^2 \;=\; -2\left(|\mu|^2 + m_{H_u}^2\right) + \text{small loop corrections} \;+\; \mathcal{O}(1/\tan^2\beta).$$

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

The problem: in mSUGRA, one typically finds $-m_{H_u}^2 \gg m_Z^2$, so percent level fine-tuning of μ appears to be required.

Why does this happen, and how can we “fix” it?

Taking mSUGRA near the GUT scale predicts a hierarchical mass spectrum at the TeV scale:



This hierarchy is mostly the gluino’s fault.

More precisely. . .

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)

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

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

If one takes a smaller gluino mass, 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.

There are lots of ways that M_3/M_2 could be smaller than in mSUGRA.

For example, suppose the F terms that break SUSY include both a singlet and an adjoint of $SU(5)$. Then at the GUT scale, one can parametrize:

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

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

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

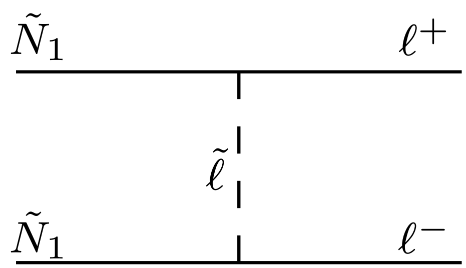
In any case, for $M_3/M_2 \ll 1$ at the GUT scale, the result is a "compressed" SUSY spectrum, with a smaller ratio of the masses of the heaviest SUSY particle and the LSP.

Now let's switch gears and consider dark matter.

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

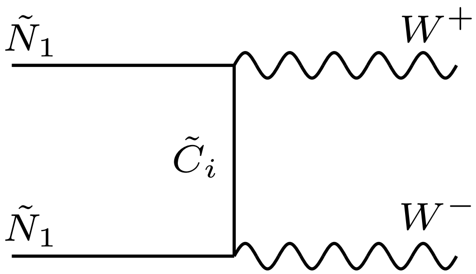
In much of SUSY parameter space, the predicted thermal $\Omega_{\rm DM} h^2$ comes out too large. A mechanism for efficient annihilation of LSPs in the early universe is needed. Possibilities include:

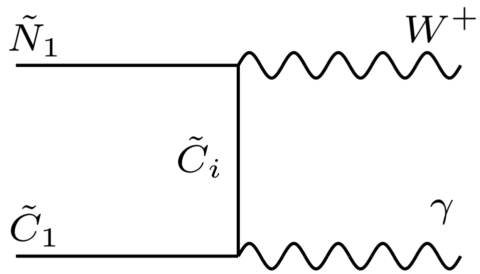
1) "Bulk region": LSPs annihilate through slepton exchange.

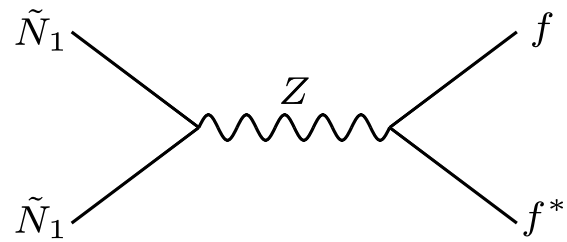


In mSUGRA, it is tough to accomodate this and LEP2 bounds at the same time.

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

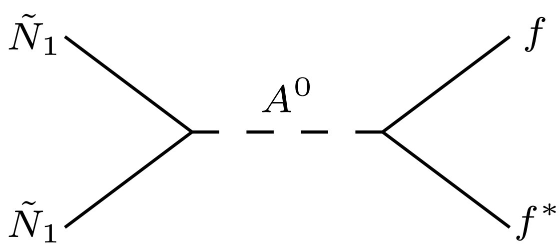






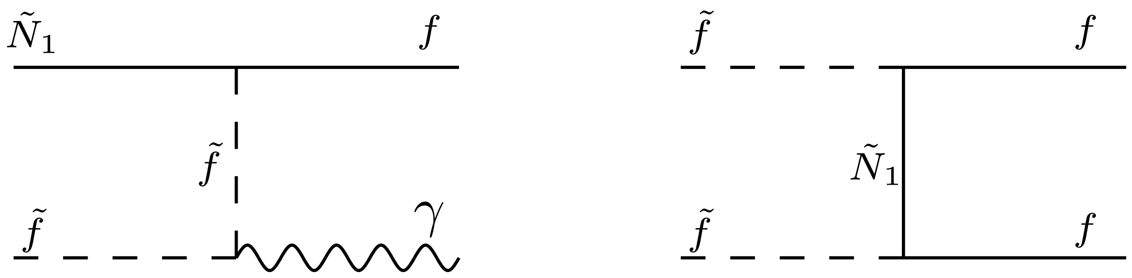
Need to get μ just right.

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

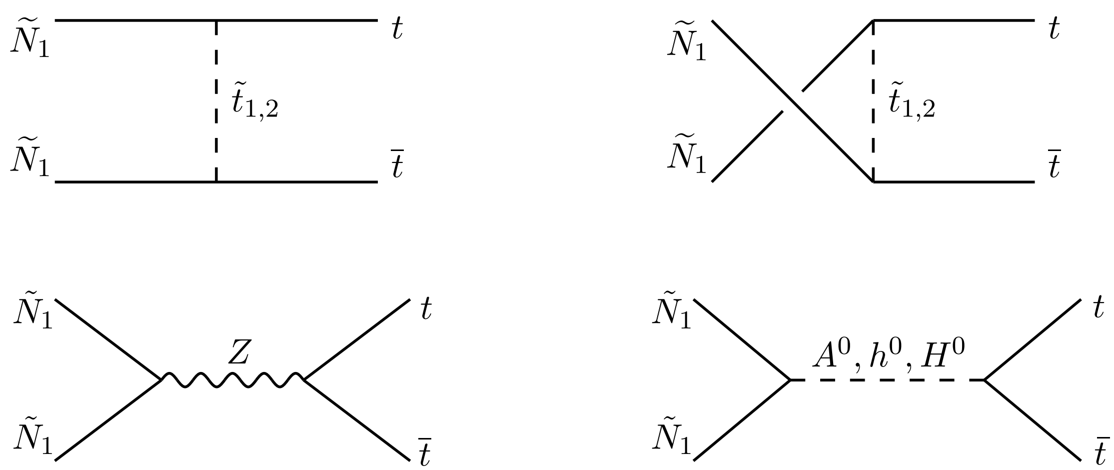


Need a small sfermion-LSP mass difference, tuned just right.

In Compressed Supersymmetry, 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 $\tilde{N}_1\tilde{N}_1 \to t\bar{t}$:



In Compressed Supersymmetry, the $\tilde{t}_1$ exchange dominates.

Note no p-wave suppression because of large m_t.

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

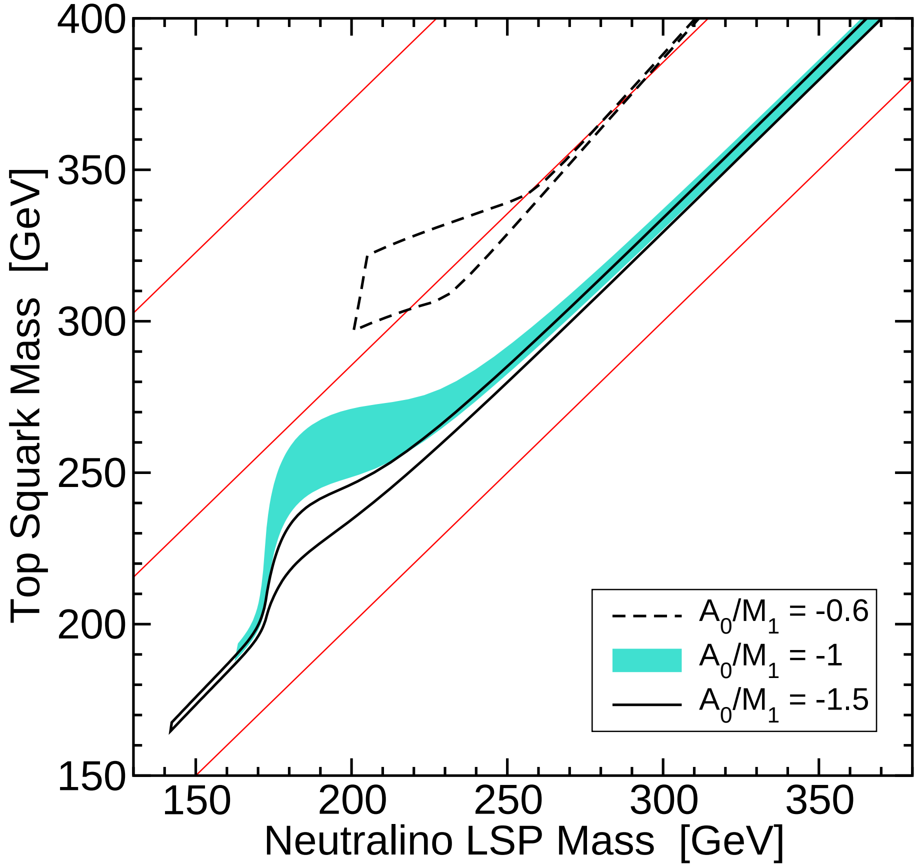
$$m_t \;<\; m_{\tilde{N}_1} \;\lesssim\; m_t + 100\,\text{GeV},$$
$$m_{\tilde{N}_1} + 25\,\text{GeV} \;\lesssim\; m_{\tilde{t}_1} \;\lesssim\; m_{\tilde{N}_1} + 100\,\text{GeV}.$$

In the following, I impose the constraint on thermal dark matter:

$$\Omega_{\rm DM} h^2 = 0.11 \pm 0.02$$

computed using `micrOMEGAs` (Belanger, Boudjema, Pukhov, Semenov).

Allowed regions in the $m_{\tilde{t}_1}$, $m_{\tilde{N}_1}$ plane for $C_{24} = 0.21$:



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

Below upper red line, $\tilde{t}_1 \to t\tilde{N}_1$ is forbidden.

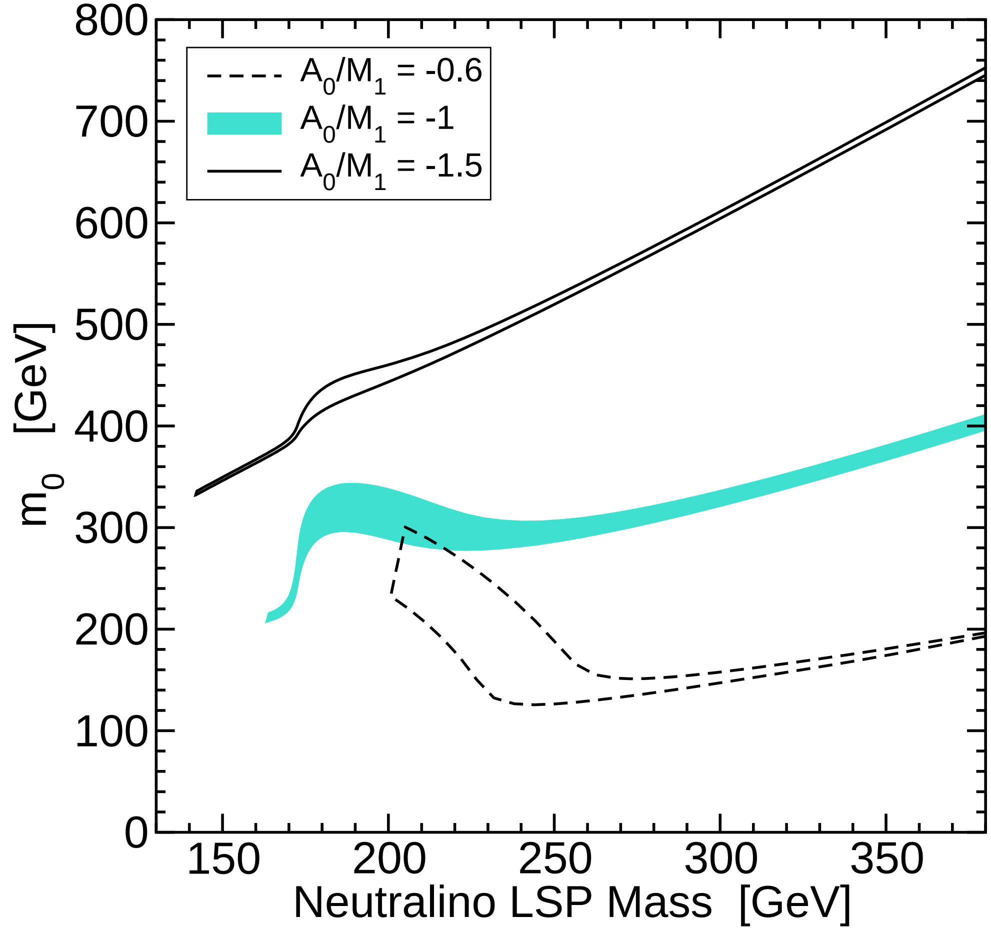
Below middle red line, $\tilde{t}_1 \to Wb\tilde{N}_1$ is also forbidden.

Below lowest red 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:

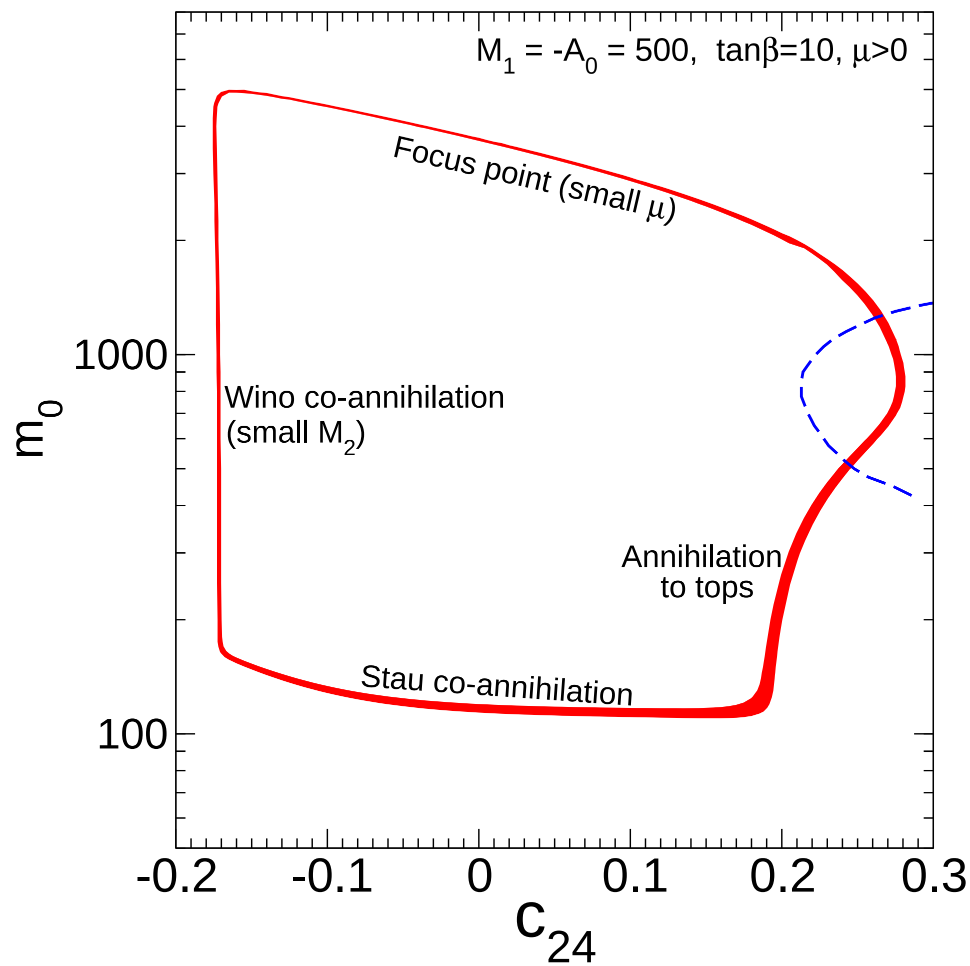


In these models, **all** soft SUSY-breaking mass parameters are less than $\hat{M}_1$, $\hat{M}_2$.

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

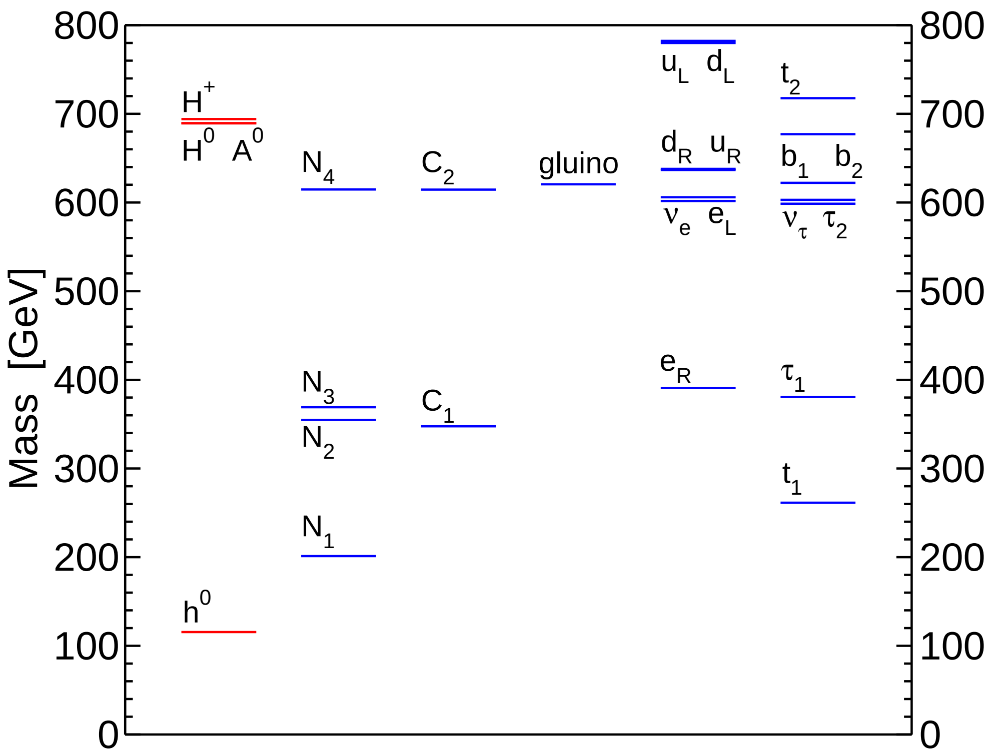
How is this related to other dark-matter allowed regions?

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.



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

Typical features of a Compressed SUSY spectrum:



Important decays for hadron colliders:

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

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

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

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

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.

Compressed SUSY: the gluino mass parameter M_3 is taken much smaller than the wino mass parameter M_2 near the GUT scale.

- Ratio of heaviest to lightest superpartner masses is reduced compared to mSUGRA.

- Lessens the SUSY little hierarchy problem

  Overlaps with the MSSM “Golden Region” of M. Perelstein and C. Spethmann

- Naturally allows the correct dark matter thermal relic abundance $0.09 < \Omega_{\rm CDM} h^2 < 0.13$ by top-squark-mediated LSP annihilation in the early universe: $\tilde{N}_1 \tilde{N}_1 \rightarrow t\bar{t}$.

- Has distinctive LHC phenomenology

  SPM, hep-ph/0703097, 0707.2812, 0801.0237,

  Baer, Box, Park, Tata 0707.0618, Hubisz, Lykken, Pierini, Spiropulu 0805.2398

In the following, I will consider a Model Line with:

$C_{24} = 0.21$,

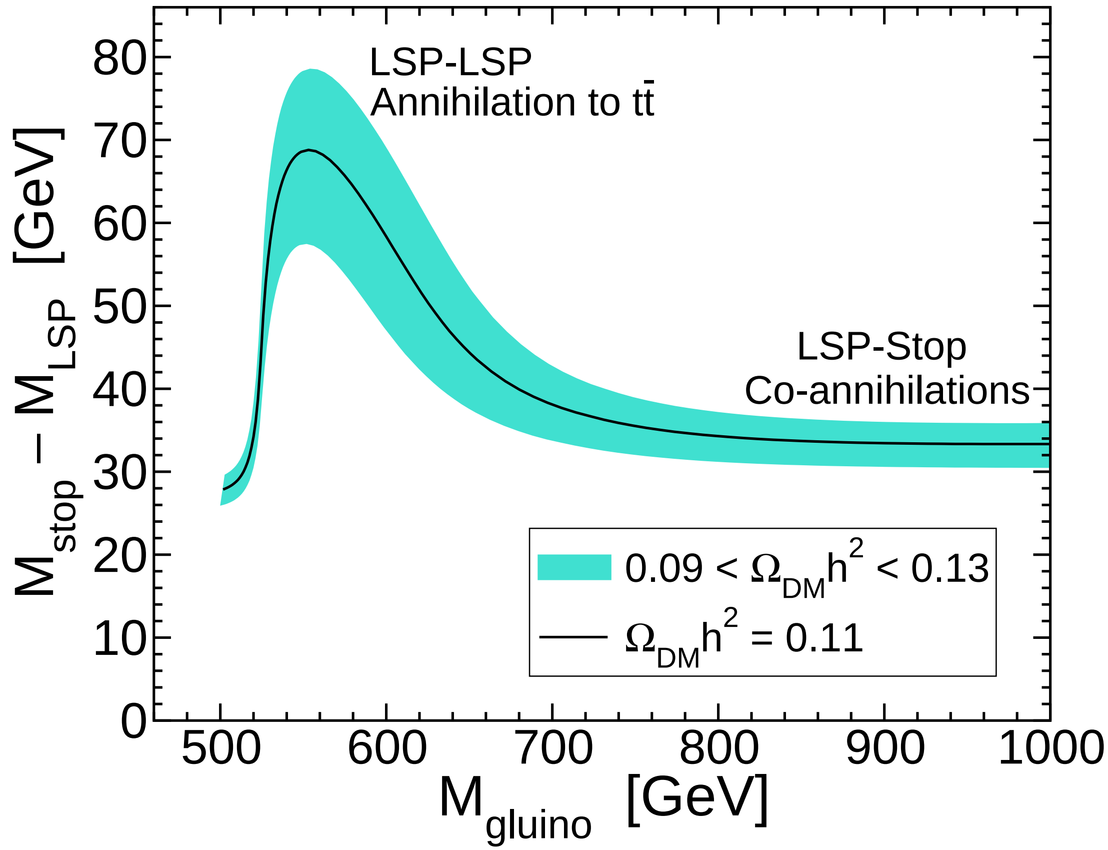
M_1 varying,

$\tan\beta = 10$, $\mu > 0$, $A_0/M_1 = -1$,

m_0 is adjusted to give the right amount of dark matter.

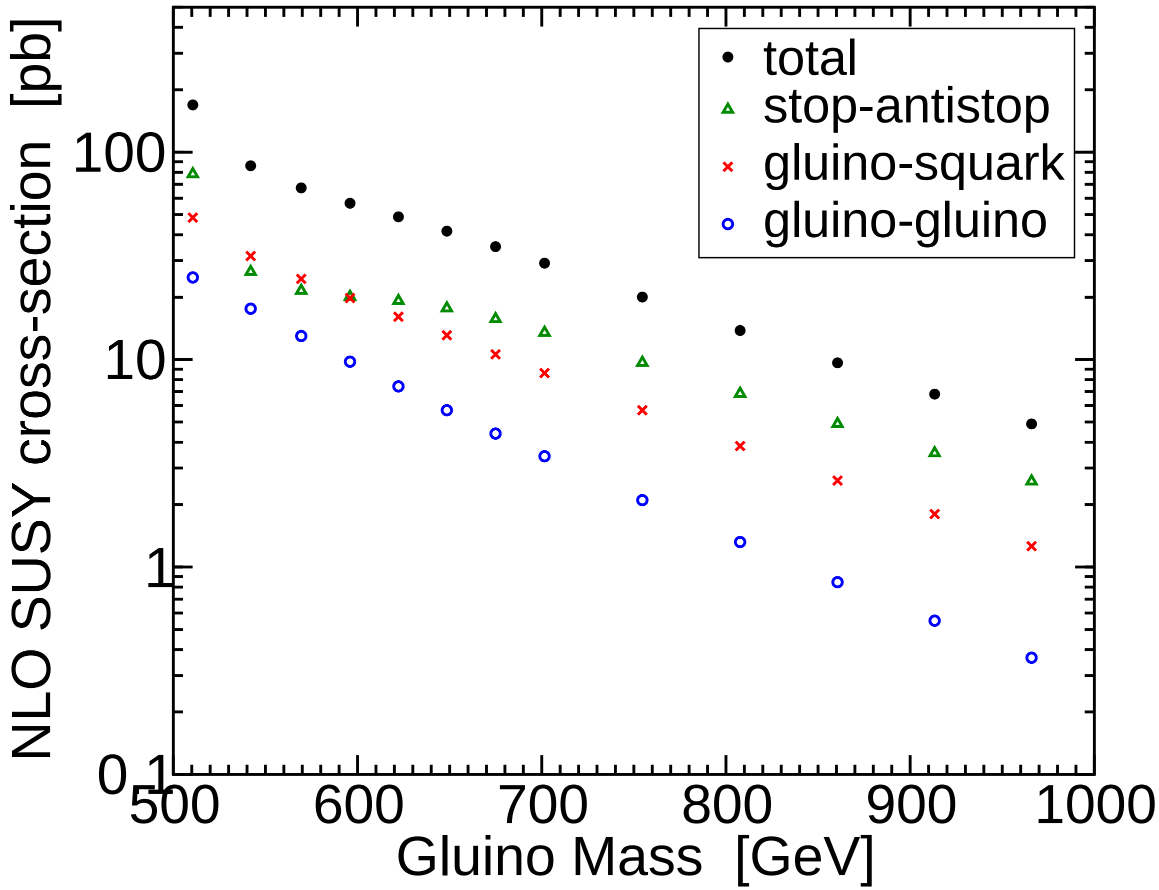
Everywhere on this model line, BR($\tilde{t}_1 \rightarrow c\tilde{N}_1$) = 100%.

Mass difference $M_{\tilde{t}_1}$ - $M_{\tilde{N}_1}$ for the dark matter allowed region of the Model Line:



The $\tilde{N}_1\tilde{N}_1 \to t\bar{t}$ "bulge" region has enhanced detection efficiency at the LHC, because the larger mass difference gives harder jets from $\tilde{t}_1 \to c\tilde{N}_1$.

Total SUSY production rates at the 14 TeV LHC:



Early discovery with jets + $E_T^{\rm miss}$ should be no problem.

But then what?

Compressed SUSY presents some challenges:

- Direct top-squark pair production is a tough signal
- Sleptons, winos, higgsinos nearly decouple from LHC
- No dilepton mass edges
- Few isolated leptons except from top decays

Distinctive LHC signal:

$$pp \to \tilde{g}\tilde{g} \to \begin{cases} t\,\overline{t}\,\tilde{t}_1\,\tilde{t}_1^* \to t\,\overline{t}\,c\,\overline{c} + E_T^{\rm miss} & (50\%) \\ t\,t\,\tilde{t}_1^*\,\tilde{t}_1^* \to t\,t\,\overline{c}\,\overline{c} + E_T^{\rm miss} & (25\%) \\ \overline{t}\,\overline{t}\,\tilde{t}_1\,\tilde{t}_1 \to \overline{t}\,\overline{t}\,c\,c + E_T^{\rm miss} & (25\%) \end{cases}$$

Due to the Majorana gluino, get Same-Sign dileptons, two b jets, and other jets from the top-squark decays:

$$\ell^+\ell^+ bb + {\rm jets} + E_T^{\rm miss},$$
$$\ell^-\ell^- bb + {\rm jets} + E_T^{\rm miss}$$

(I don't assume that the charm jets can be tagged, although likelihoods from heavy flavor tag algorithms will provide some information.)

Kraml and Raklev hep-ph/0512284 studied the same signal for other models, and I copy some of their ideas in the following. Their models differed in having $\tilde{t}_1$ much lighter (less than m_t), and other squarks much heavier.

In Compressed SUSY,

$$
\begin{aligned}
pp &\rightarrow \tilde{q}\tilde{g} \rightarrow q\tilde{g}\tilde{g} \\
pp &\rightarrow \tilde{q}\tilde{q} \rightarrow qq\tilde{g}\tilde{g}
\end{aligned}
$$

are also important sources of SS dilepton + b jet events.

This is an added challenge for reconstructing SUSY events.

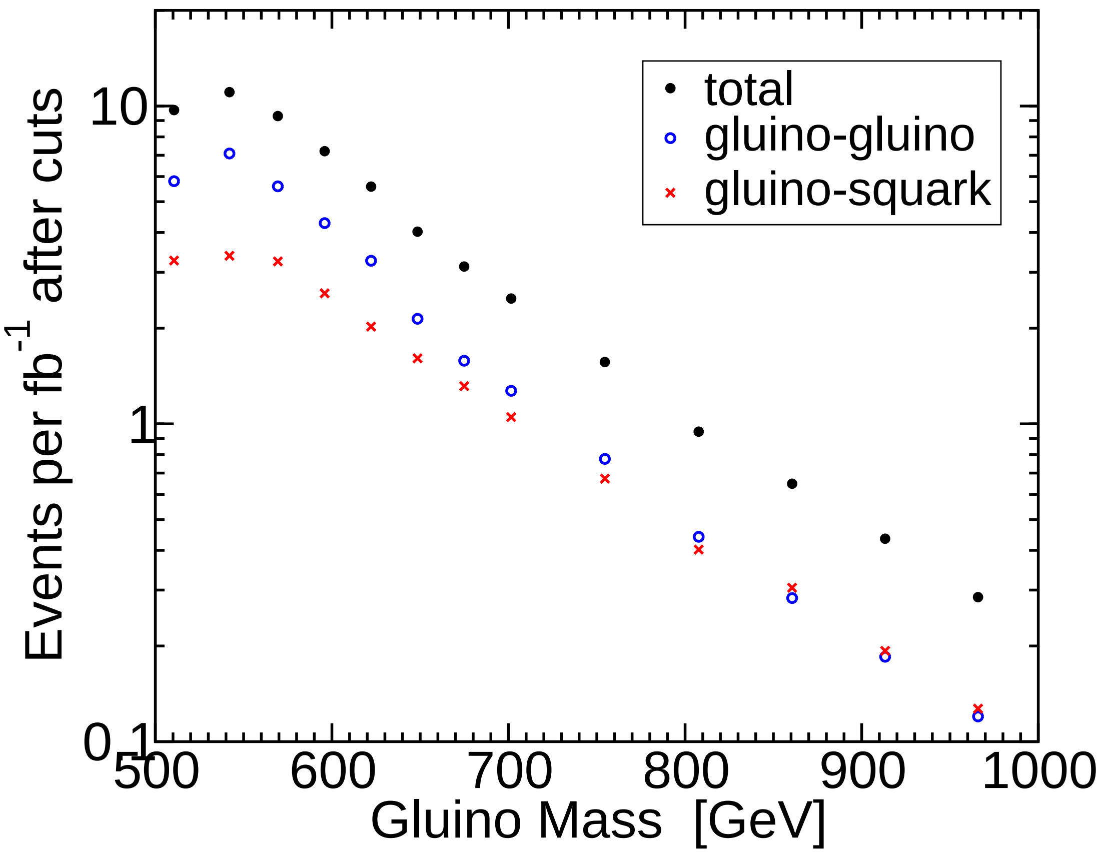
Use MadGraph/MadEvent $\longrightarrow$ Pythia $\longrightarrow$ PGS4 for event generation and detector simulation. (No jet energy scale corrections.)

Require

- Exactly 2 Same-Sign isolated leptons $(\ell = e, \mu)$ with $p_T > 20$ GeV
- At least two b-tagged jets each with $p_T > 50$ GeV
- At least two more jets with $p_T > 50, 35$ GeV
- Two Same-Sign lepton-b pair assignments, each consistent with leptonic top decay: $M(\ell b) < 160$ GeV
- $E_T^{\rm miss} > 100$ GeV

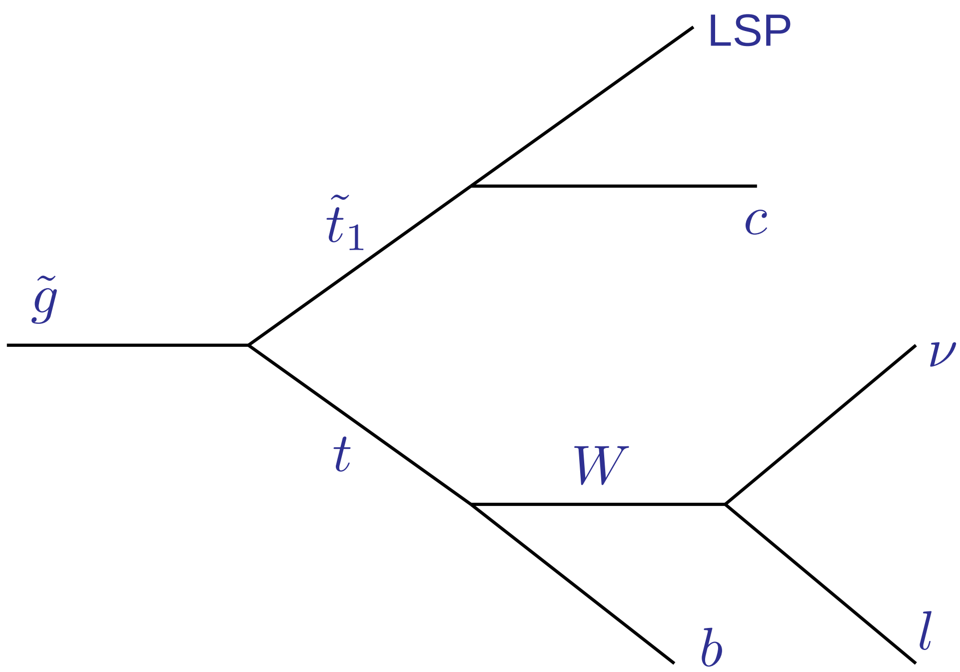
With these cuts, the Standard Model background is mostly $t\bar{t}$: less than 1 event/fb^{-1}. However, depends crucially on fake rates and wrong-sign assignment rates for leptons, which are difficult to anticipate before data taking.

Signal rates, after cuts, for $\ell^{\pm}\ell^{\pm}bbjj + E_T^{\rm miss}$



Detection prospects will depend on how well Same-Sign lepton backgrounds can be understood.

Look at the mass endpoints of visible decay products of the gluino: b, l, c.



The top decay has:

$$M^2(bl)_{\max} \quad = \quad m_t^2 - m_W^2 .$$

No new information on masses, but allows b jets to be paired with leptons.

The other endpoints contain information on SUSY masses, but are not independent:

$$
\begin{aligned}
M^2(lc)_{\max} &= \frac{1}{2}\Big(1 - \frac{m^2_{\tilde{N}_1}}{m^2_{\tilde{t}_1}}\Big)\Big[m^2_{\tilde{g}} - m^2_{\tilde{t}_1} - m_t^2 + \lambda^{1/2}(m^2_{\tilde{g}}, m^2_{\tilde{t}_1}, m_t^2)\Big] \\
M^2(bc)_{\max} &= \Big(1 - \frac{m_W^2}{m_t^2}\Big) M^2(lc)_{\max} \\
M^2(blc)_{\max} &= M^2(lc)_{\max} + m_t^2 - m_W^2
\end{aligned}
$$

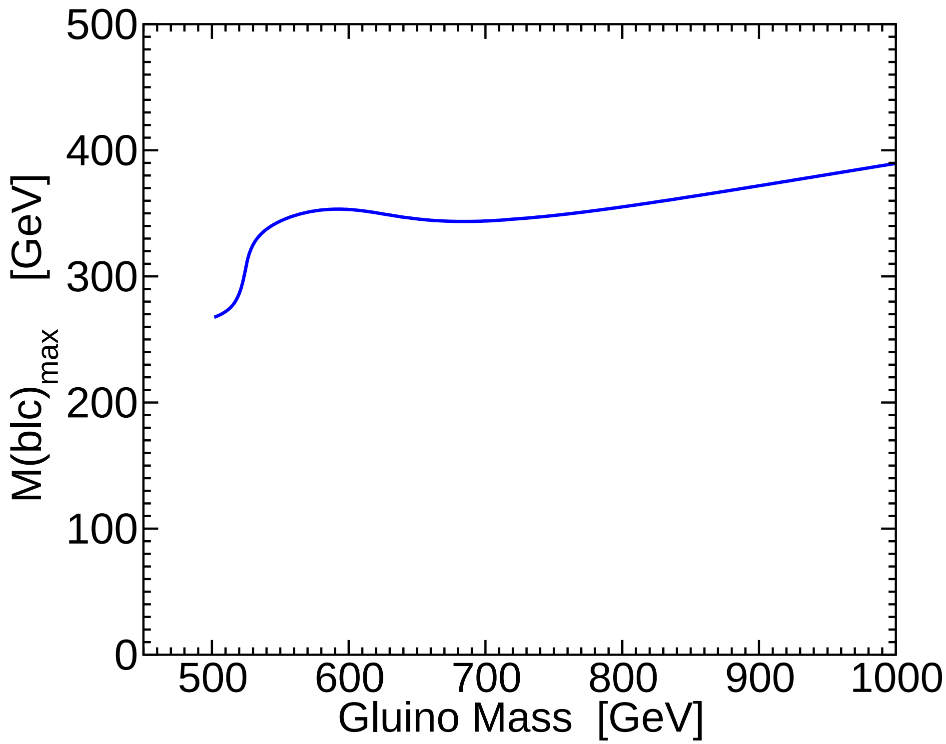
So the endpoints all contain the same information about the gluino, stop, and LSP masses.

But, different events populate the near-endpoint regions of these distributions.

Unfortunately, the $M^2(lc)$ distribution is very shallow near the endpoint, so concentrate on the latter two.

Endpoints: Good News and Bad News.

First, the Bad News. In principle, the endpoints carry information about the gluino, top-squark and LSP masses. But in practice they depend only very weakly on the model!



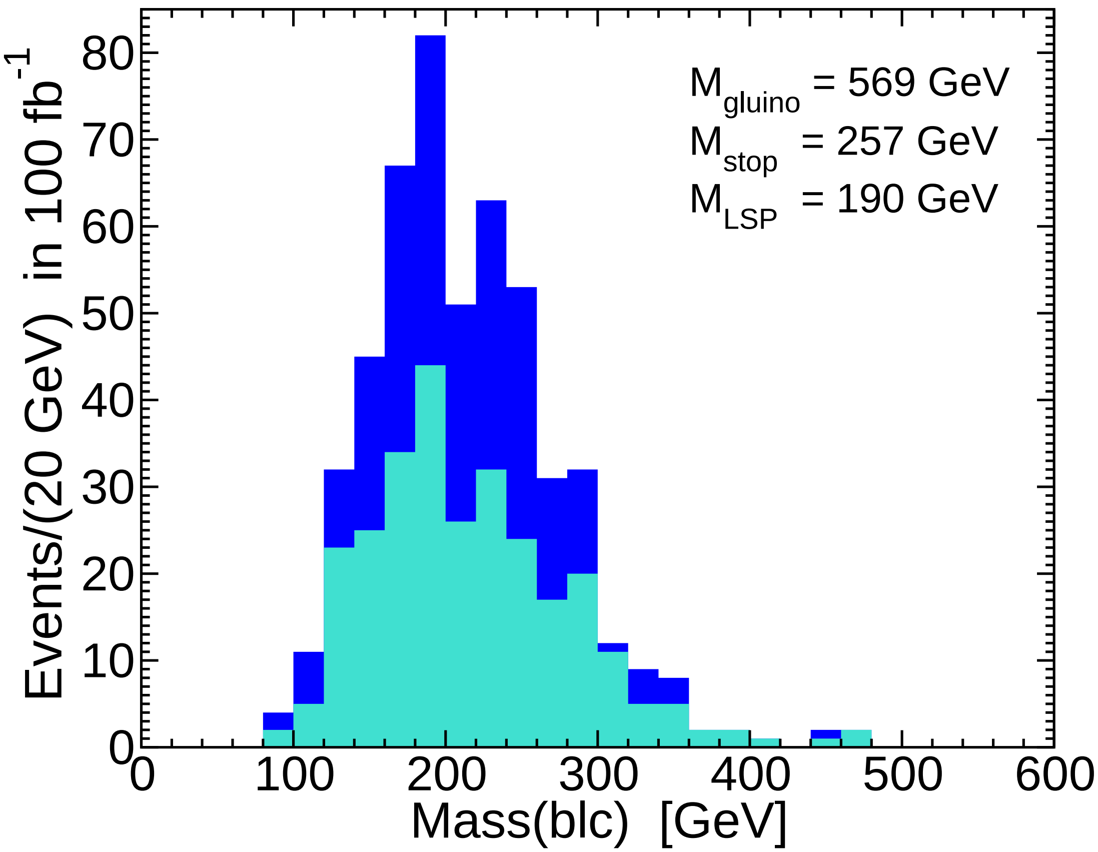
However, try it anyway. To get as clean a sample as possible:

Select events with same cuts as before, and a **unique** pairing of b-jets with leptons so that both pairs have $M(bl) < 180$ GeV.

For each (bl) pair, choose the jet with the smallest $M(blc)$ as the charm candidate. Require $p_T(j_c) > 35$ GeV. No charm tagging is used.

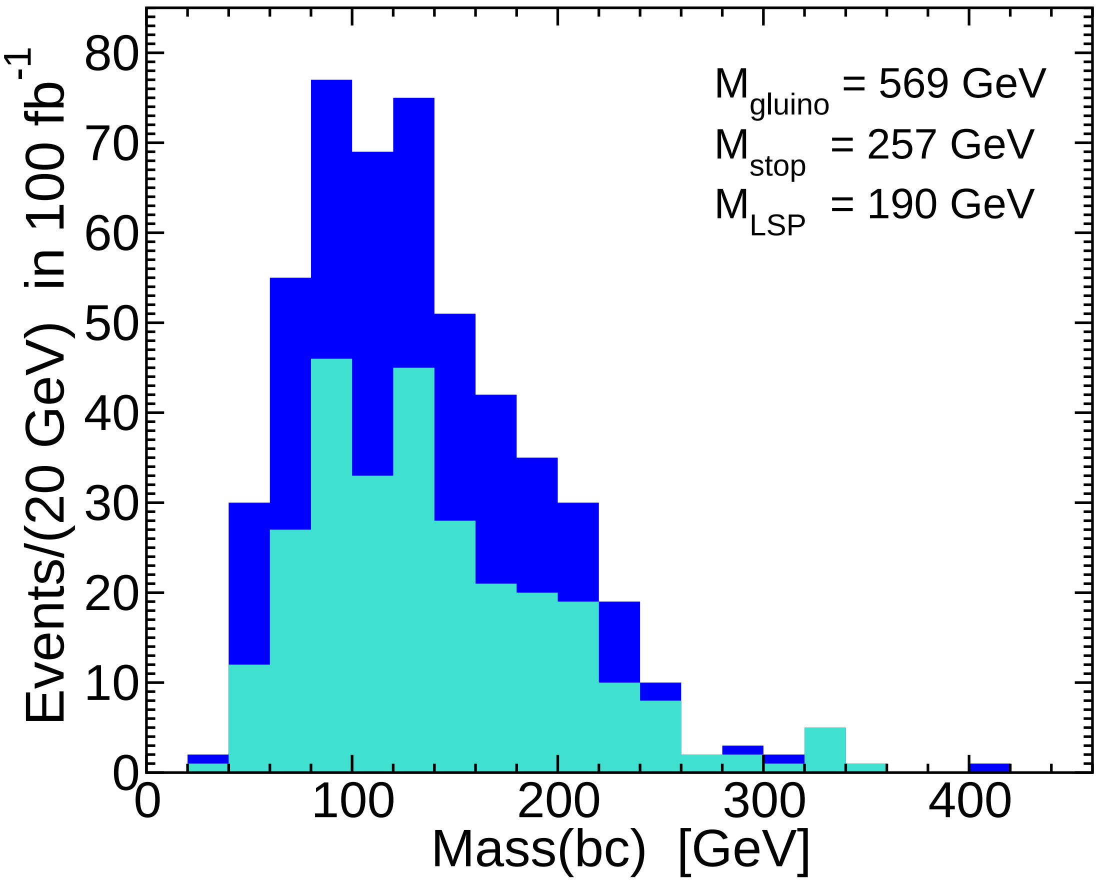
Look for the endpoints in both $M(blc)$ and $M(bc)$.

For 100 fb^{-1}, and a model with $M_{\rm gluino} = 569$ GeV, with a nominal endpoint $M(blc)_{\rm max} = 350$ GeV:

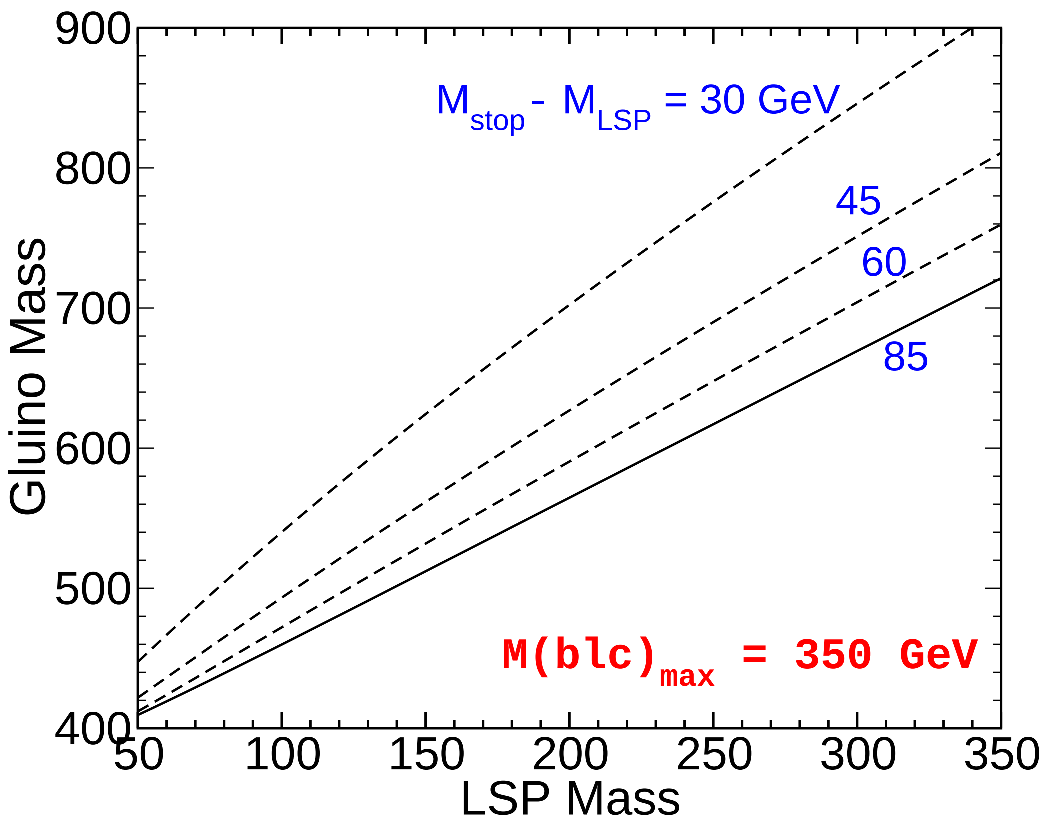


Light blue = part from gluino pair production

Same model, but $M(bc)_{\max}$ distribution, with a nominal endpoint of 279 GeV:



The Good News: if one can establish the $M(blc)_{\max}$ endpoint:

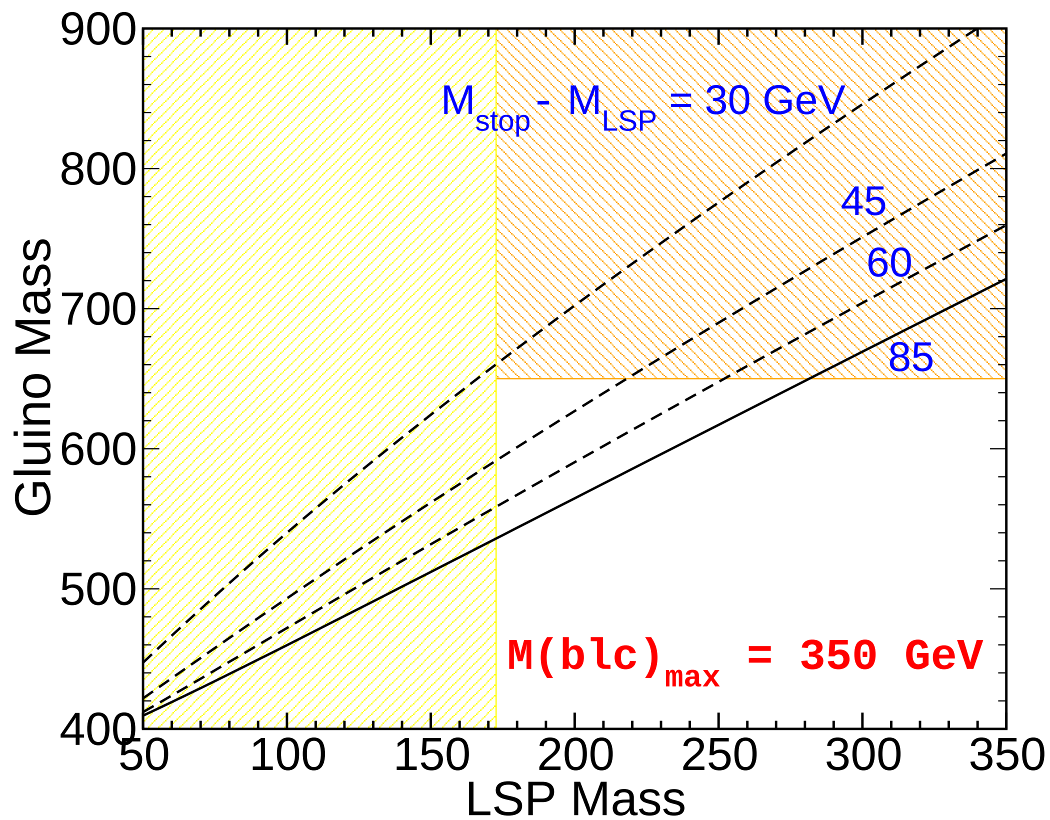


If the $\tilde{g} \to t\tilde{t}_1 \to blc\nu\tilde{N}_1$ interpretation is right, we must be above the solid line.

Note if $M(blc)_{\max}$ is larger, the curves move up.

Add model-dependent information (prejudices?):

- Dark matter annihilation from $\tilde{N}_1 \tilde{N}_1 \rightarrow t\bar{t}$
- At least 4 events per fb^{-1} observed



In the classic collider signatures for SUSY,

Invisible LSPs $\longrightarrow$ Missing Energy $\longrightarrow$ No Mass Peaks

Compressed SUSY provides an exception, because of the long lifetime of $\tilde{t}_1$:

Stoponium $= \eta_{\tilde{t}} =$ s-wave $\tilde{t}_1^* \tilde{t}_1$ bound state

Drees and Nojiri 1994 proposed looking for stoponium in

$$pp \longrightarrow \eta_{\tilde{t}} \longrightarrow \gamma\gamma$$

Stoponium is very narrow, so the width is effectively that of the detector resolution for diphotons, of order 1% at CMS and ATLAS.

Stoponium in Compressed SUSY:

- is always stable enough to form
- Binding energy of $\eta_{\tilde{t}}$ is a few GeV
- $\Gamma_{\eta_{\tilde{t}}}$ is a few MeV
- $M_{\eta_{\tilde{t}}}$ between about 400 and 750 GeV
- BR$(\eta_{\tilde{t}} \to gg)$ dominates (but huge background)
- BR$(\eta_{\tilde{t}} \to \gamma\gamma) \approx 0.4\%$

The process

$$pp \to \eta_{\tilde{t}} \to \gamma\gamma$$

is clearly NOT a discovery mode for supersymmetry.

Importance is that it will give a uniquely precise measurement of the top-squark mass.

Look for a narrow diphoton mass peak against a smoothly falling background. To be conservative, I count events in a bin of width $0.04 M_{\gamma\gamma}$ centered on the putative peak.

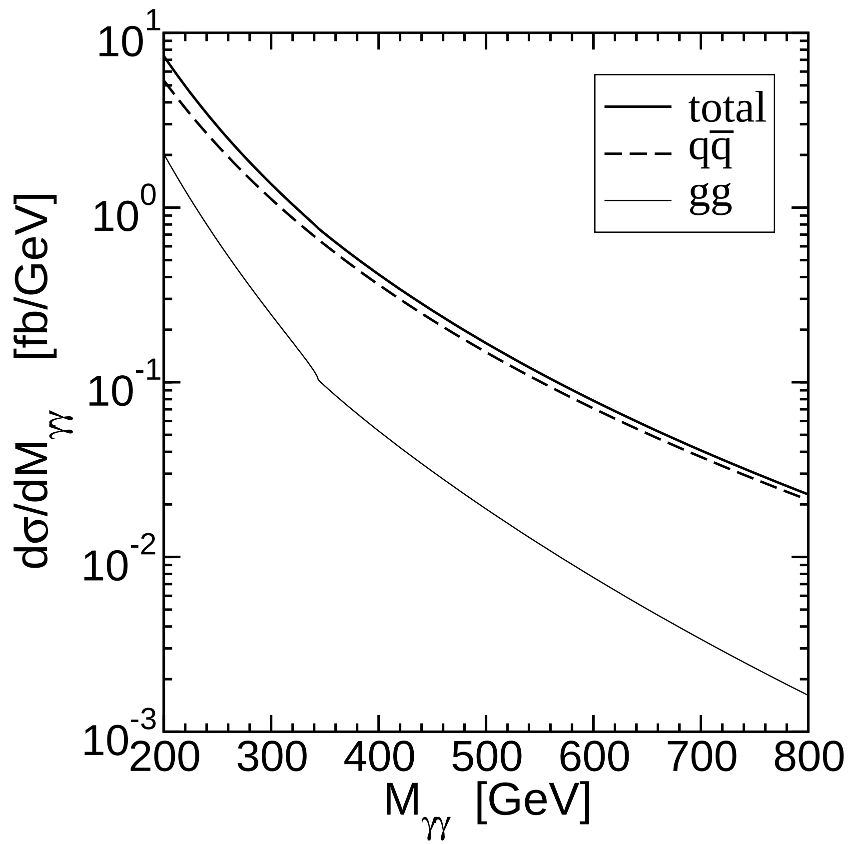
The irreducible physics backgrounds at leading order:

$$q\overline{q} \quad \longrightarrow \quad \gamma\gamma \qquad\qquad \text{(tree-level)}$$

$$gg \quad \longrightarrow \quad \gamma\gamma \qquad\qquad \text{(1-loop)}$$

Backgrounds from fakes are thought to be smaller.

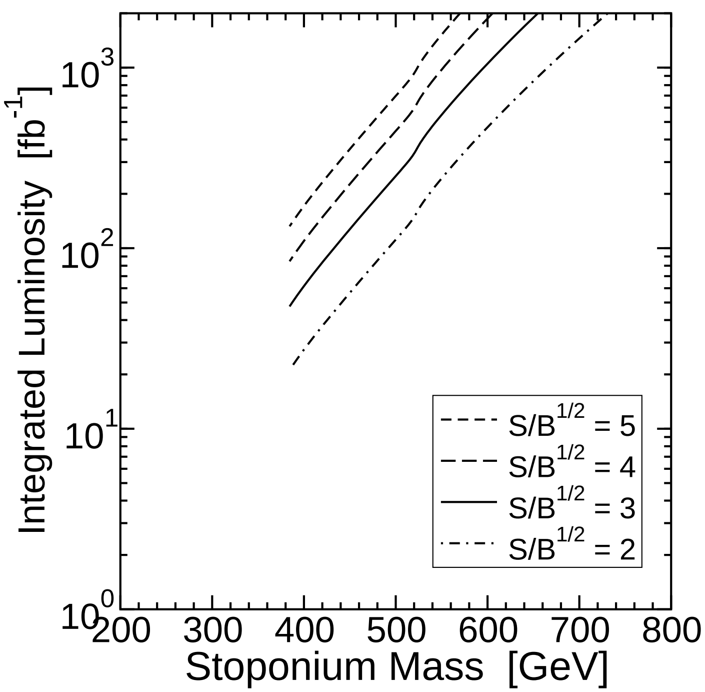
Diphoton backgrounds at LHC, at leading order, after cuts:



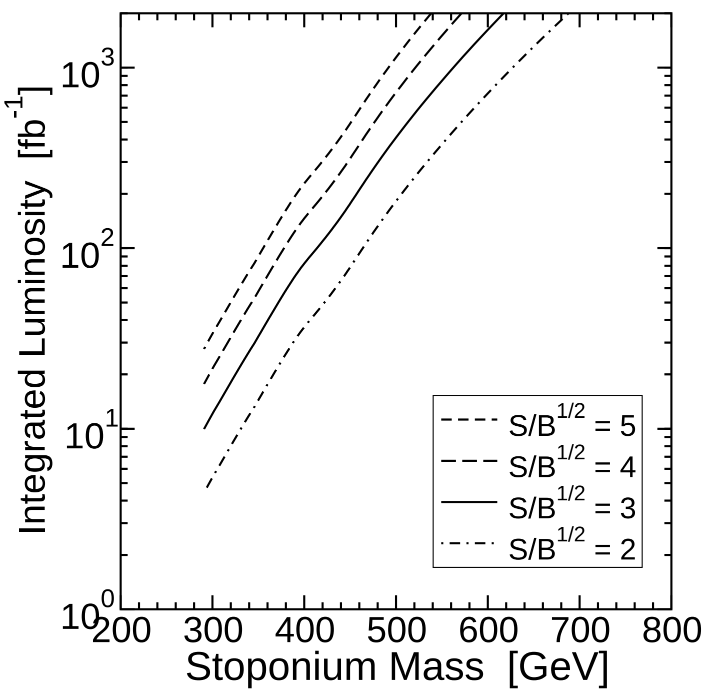
Note: actual background will be obtained from LHC data!

Luminosity needed for expected significances, for two model lines:

$C_{24} = 0.21,\ \ A_0/M_1 = -1$



$C_{24} = 0.21,\ \ A_0/M_1 = -2$



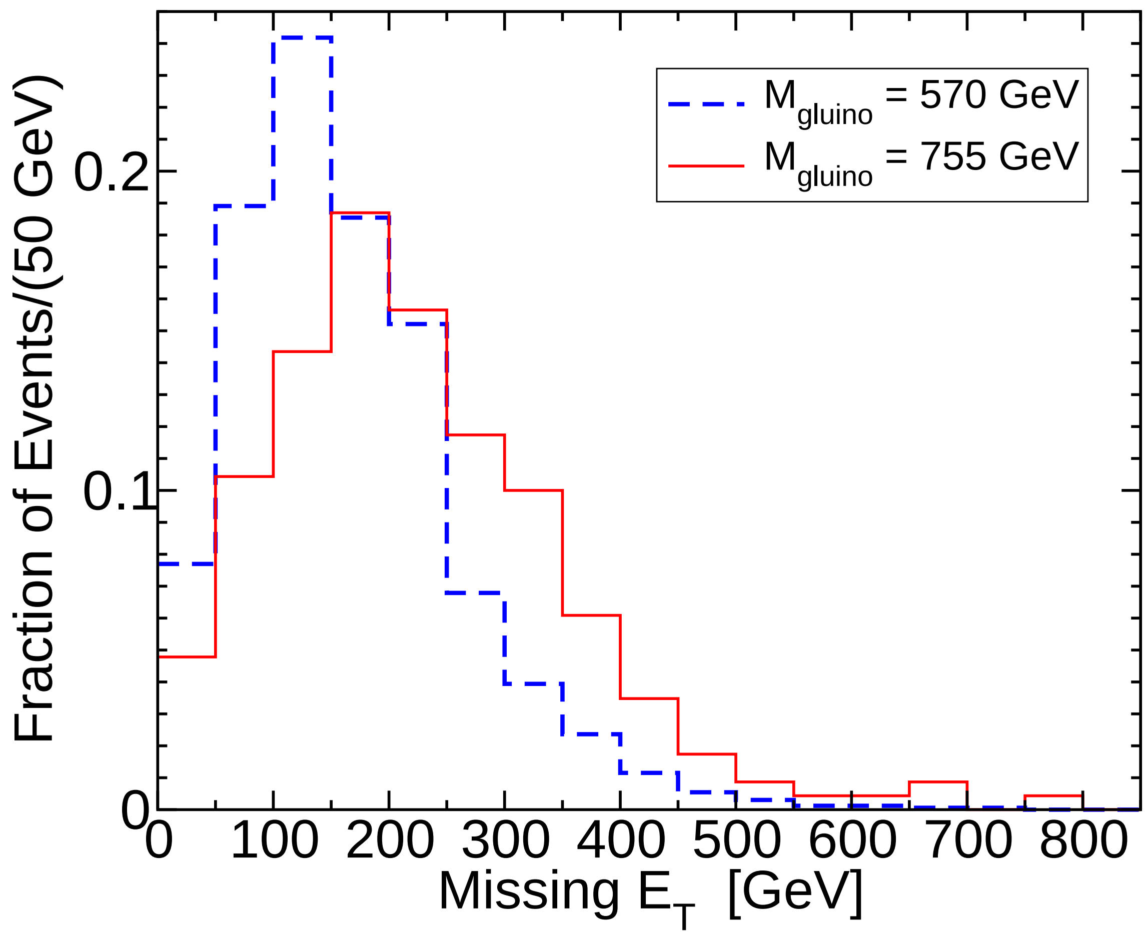
Detectability for $m_{\eta_{\tilde{t}}} = 500$ GeV will require more than 100 fb^{-1}.

For smaller $m_{\eta_{\tilde{t}}}$, a few $\times 10$ fb^{-1} might do it (if we're lucky).

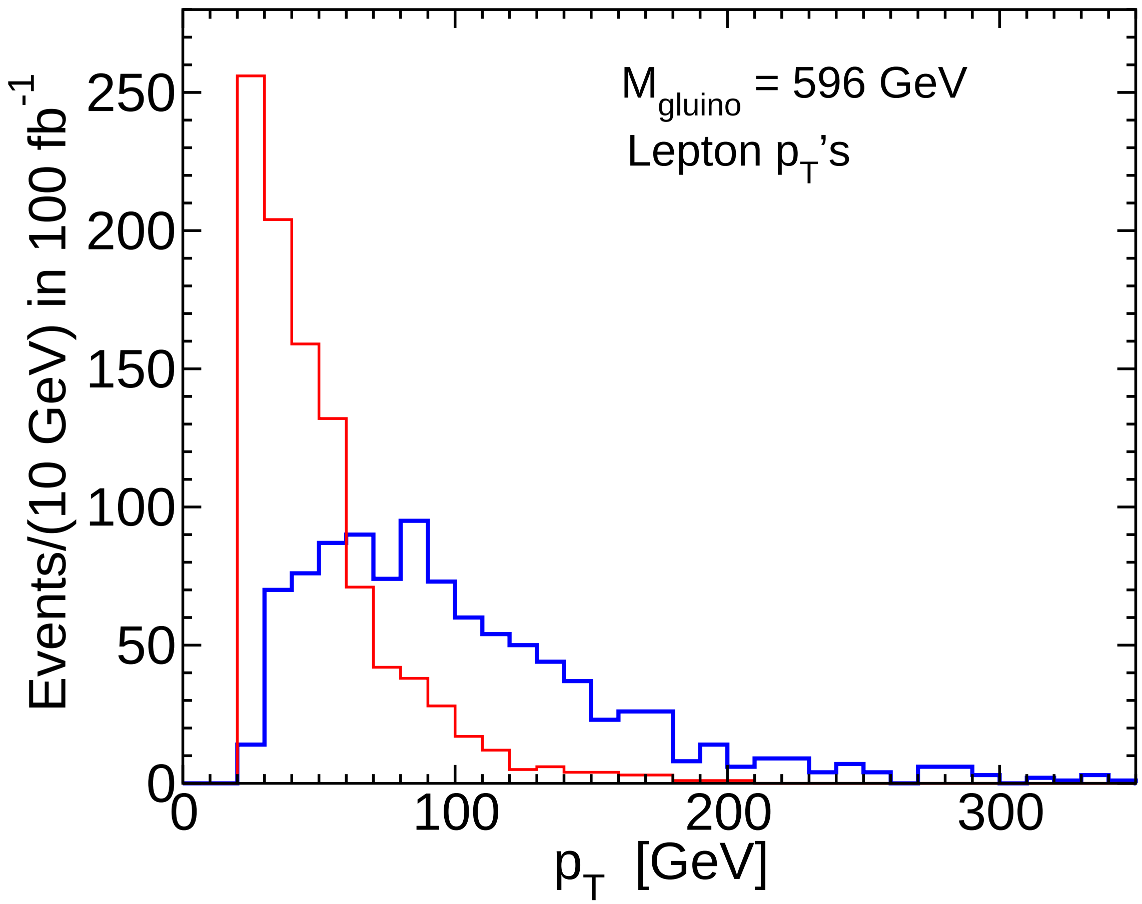
Compressed SUSY:

- gives a qualitatively distinct way of producing the correct relic abundance of dark matter
- ameliorates the SUSY little hierarchy problem
- has distinctive LHC phenomenology
  - Same-Sign tops + $E_T^{\rm miss}$
  - stoponium
  - no easy dilepton mass edges
  - (typically) no information about sleptons, winos, or higgsinos
- No visible superpartners at a $\sqrt{s} = 500$ GeV linear collider.

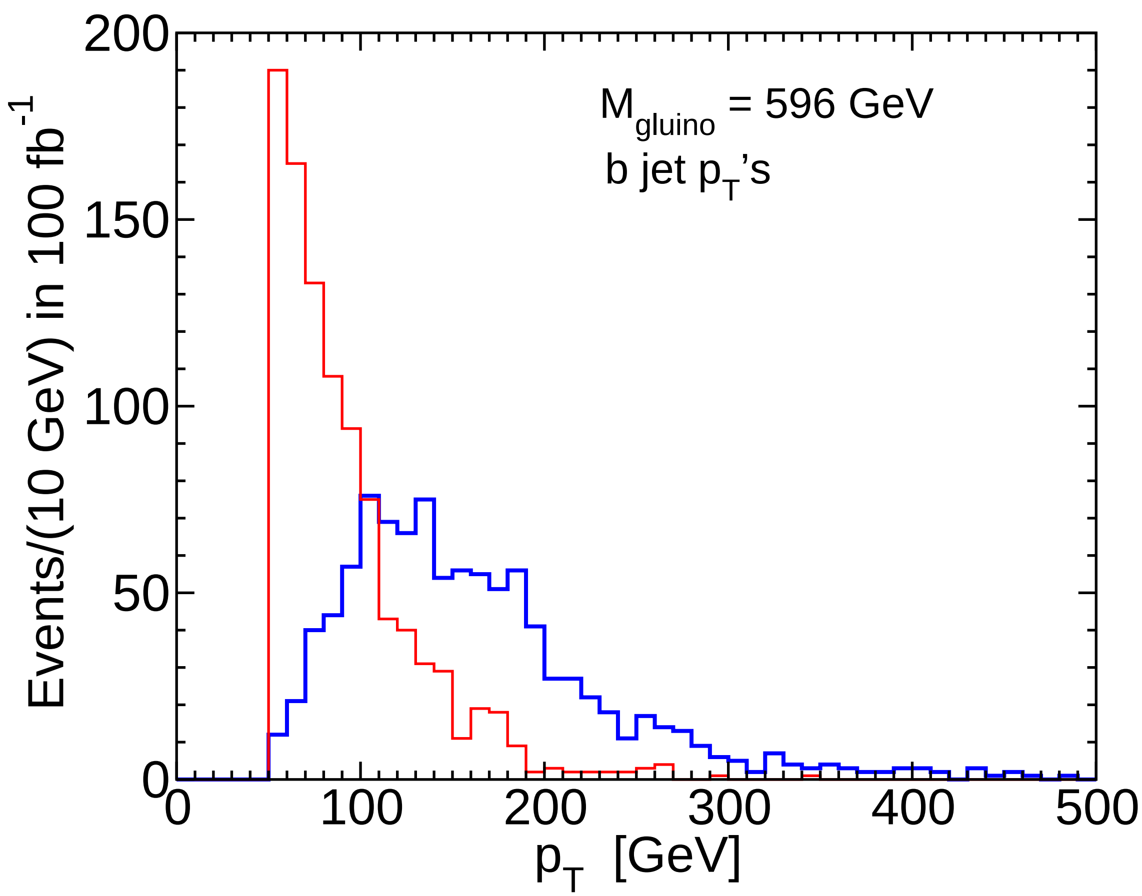
$E_T^{\rm miss}$ distribution in $bbl^+l^+ + {\rm jets} + E_T^{\rm miss}$ events:



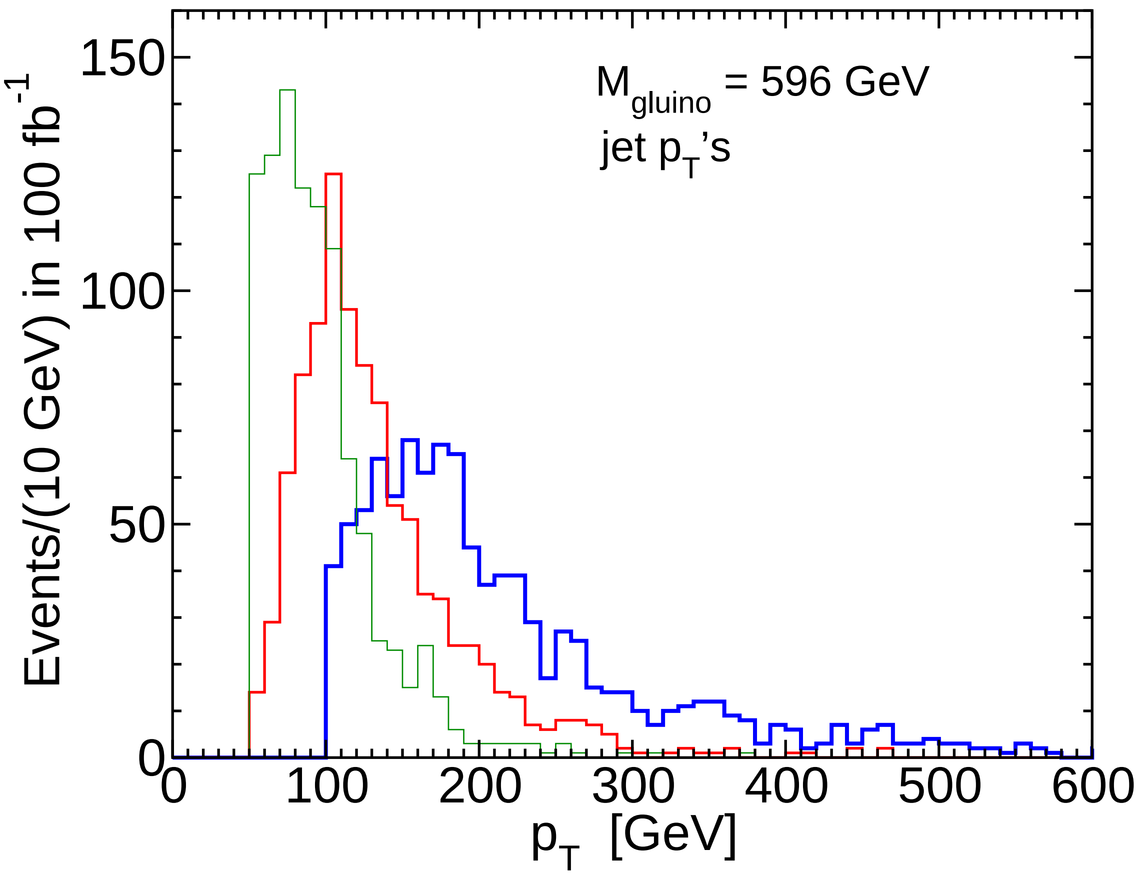
Extra slide: Lepton p_T distributions



Extra slide: b jet p_T distributions



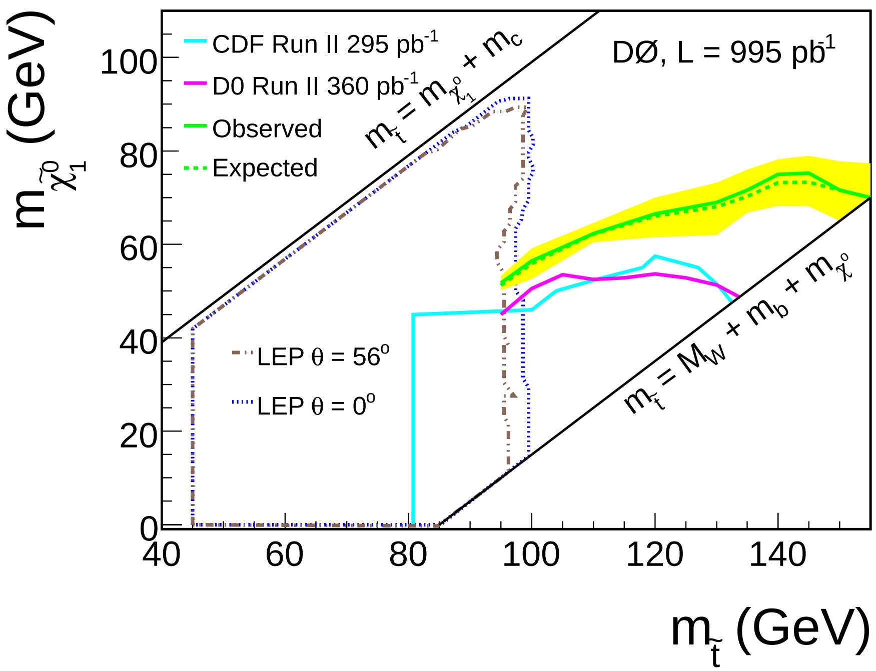
Extra slide: jet p_T distributions



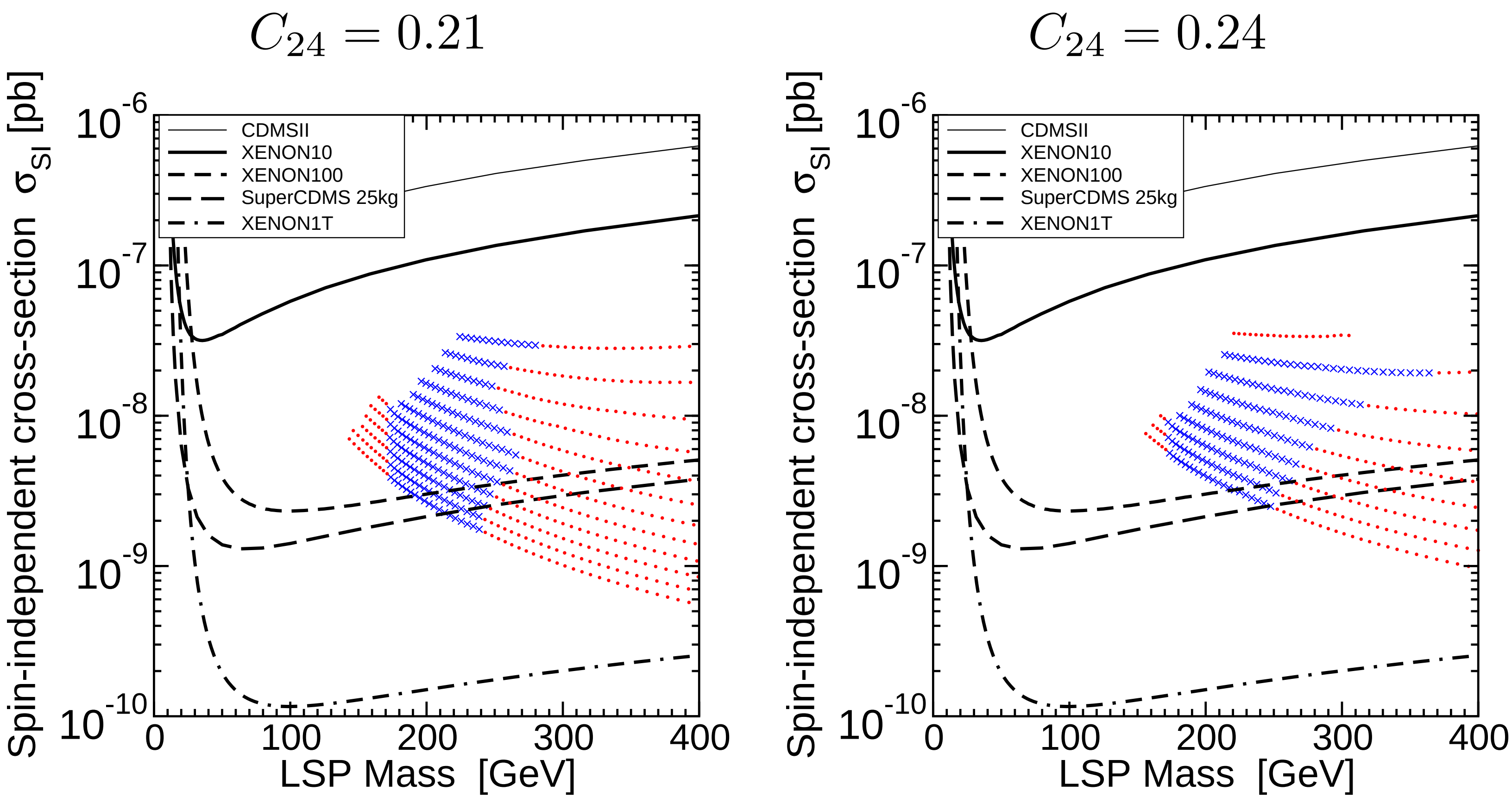
The target is here!

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:

$$p\overline{p} \rightarrow \tilde{t}_1 \tilde{t}_1^* \rightarrow c\overline{c}\tilde{N}_1 \tilde{N}_1 \rightarrow c\,\overline{c} + E_T^{\rm miss}$$



Usual Tevatron signals for SUSY, trileptons, like-sign dileptons, jets + $E_T^{\rm miss}$, all seem to be very hard or impossible. Not enough events.



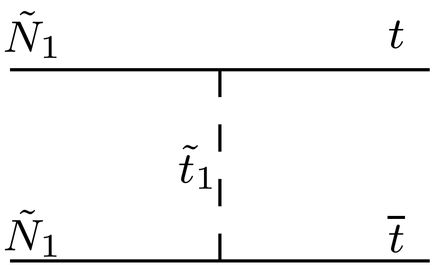
Blue X's = "bulge" annihilation-to-top models,

Red dots = stop co-annihilation models

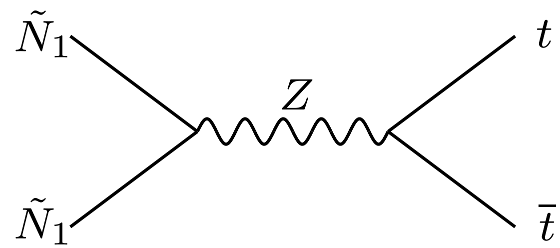
Present experiments do not constrain the scenario.

Future experiments should provide a definitive test.

Why this works: 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.