Collider aspects of supersymmetry with non-universal gaugino masses

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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

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

But even within GUT and GUT-like models, this is a very restrictive assumption.

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

MSUGRA assumes that the source SUSY breaking is a VEV

$$\langle F \rangle \neq 0$$

that is a singlet under the unified gauge group.

More generally, F could be in any representation in the symmetric product of the adjoint of the gauge group with itself, as long as the result contains a Standard Model singlet.

For $SU(5)$:

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

For $SO(10)$:

$$(\mathbf{45} \times \mathbf{45})_S = \mathbf{1} + \mathbf{54} + \mathbf{210} + \mathbf{770}$$

What happens for SO(10) ?

Ratios of gaugino masses for SU(5) and SO(10):

SU(5)	$M_1 : M_2 : M_3$
1	1 : 1 : 1
24	1 : 3 : –2
75	–5 : 3 : 1
200	10 : 2 : 1

Ellis, Enqvist, Nanopoulos, Tamvakis

Anderson et al. (Snowmass 1996)

SO(10)	SU(4) × SU(2)$_R$	$M_1 : M_2 : M_3$
1	(**1**, **1**)	1 : 1 : 1
54	(**1**, **1**)	1 : 3 : –2
210	(**1**, **1**)	$-\frac{3}{5} : 1 : 0$
	(**15**, **1**)	$-\frac{4}{5} : 0 : 1$
	(**15**, **3**)	1 : 0 : 0
770	(**1**, **1**)	$\frac{19}{10} : \frac{5}{2} : 1$
	(**1**, **5**)	1 : 0 : 0
	(**15**, **3**)	1 : 0 : 0
	(**84**, **1**)	$\frac{32}{5} : 0 : 1$

SPM, hep-ph/0903.3568

Previous papers on gaugino mass ratios in SO(10), based on hep-ph/0110332, were wrong! (See however Chakrabortty and Raychaudhuri, hep-ph/0809.2012)

[In hep-ph/0903.3568, I also give results for every other possible embedding of $SU(3)_C \times SU(2)_L \times U(1)_Y$ within $SO(10)$ or E_6.]

If the F terms that break SUSY include both a singlet and a $\mathbf{24}$ of $SU(5)$ or a $\mathbf{54}$ of $SO(10)$, then at the GUT scale, one can parametrize:

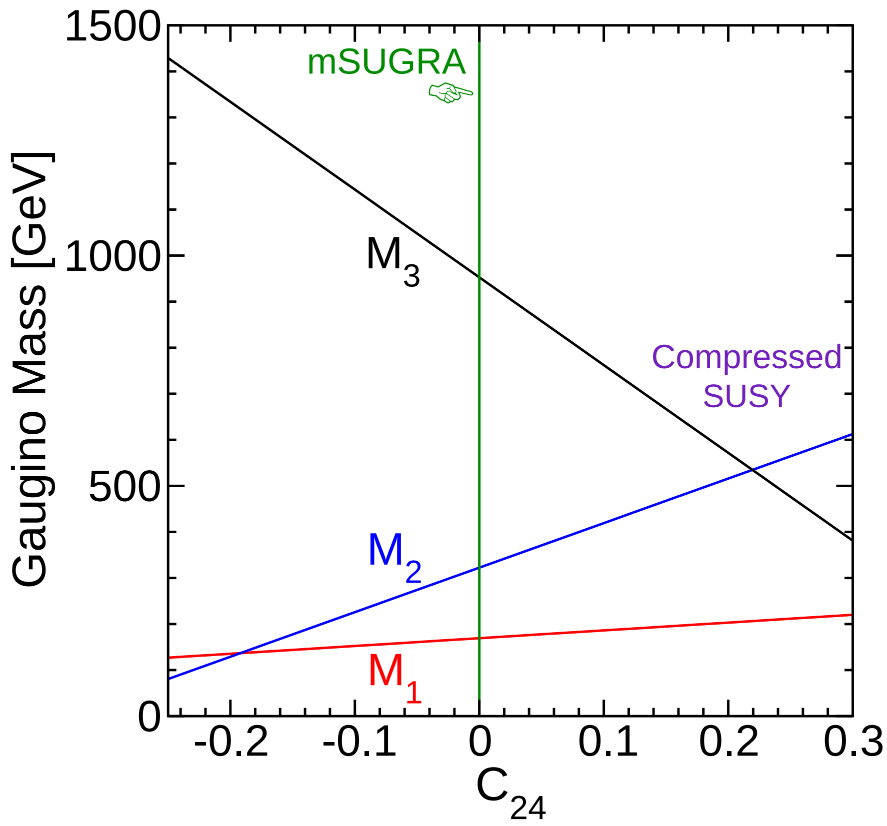
$$\begin{aligned} M_1 &= m_{1/2}(1 + C_{24}), \\ M_2 &= m_{1/2}(1 + 3C_{24}), \\ M_3 &= m_{1/2}(1 - 2C_{24}). \end{aligned}$$

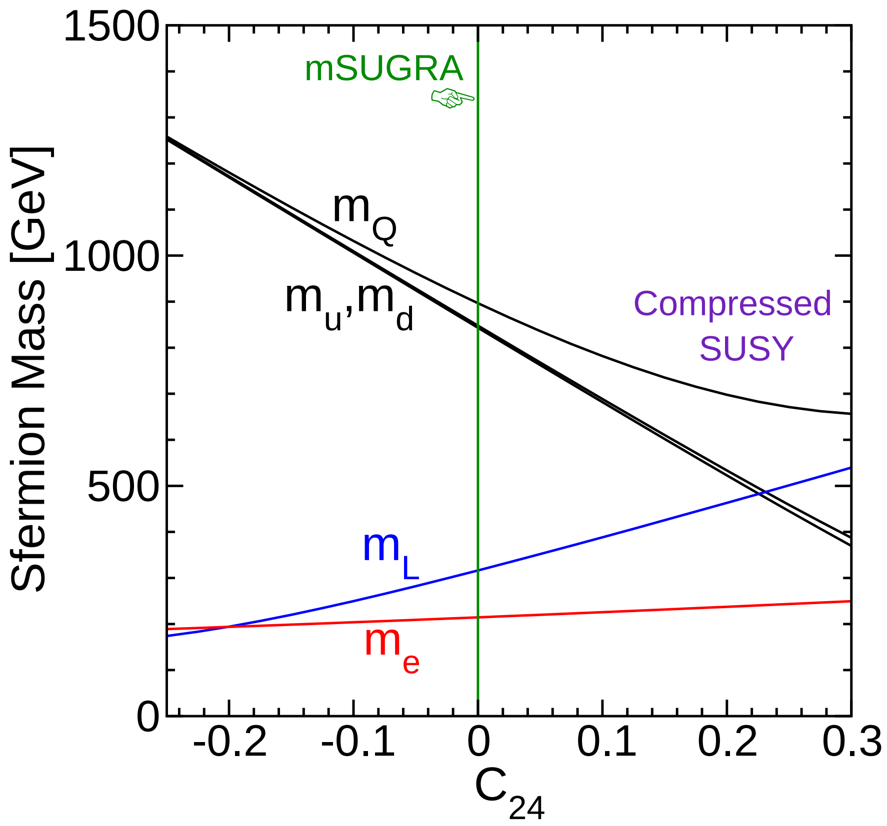
The special case $C_{24} = 0$ recovers the usual mSUGRA model.

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?

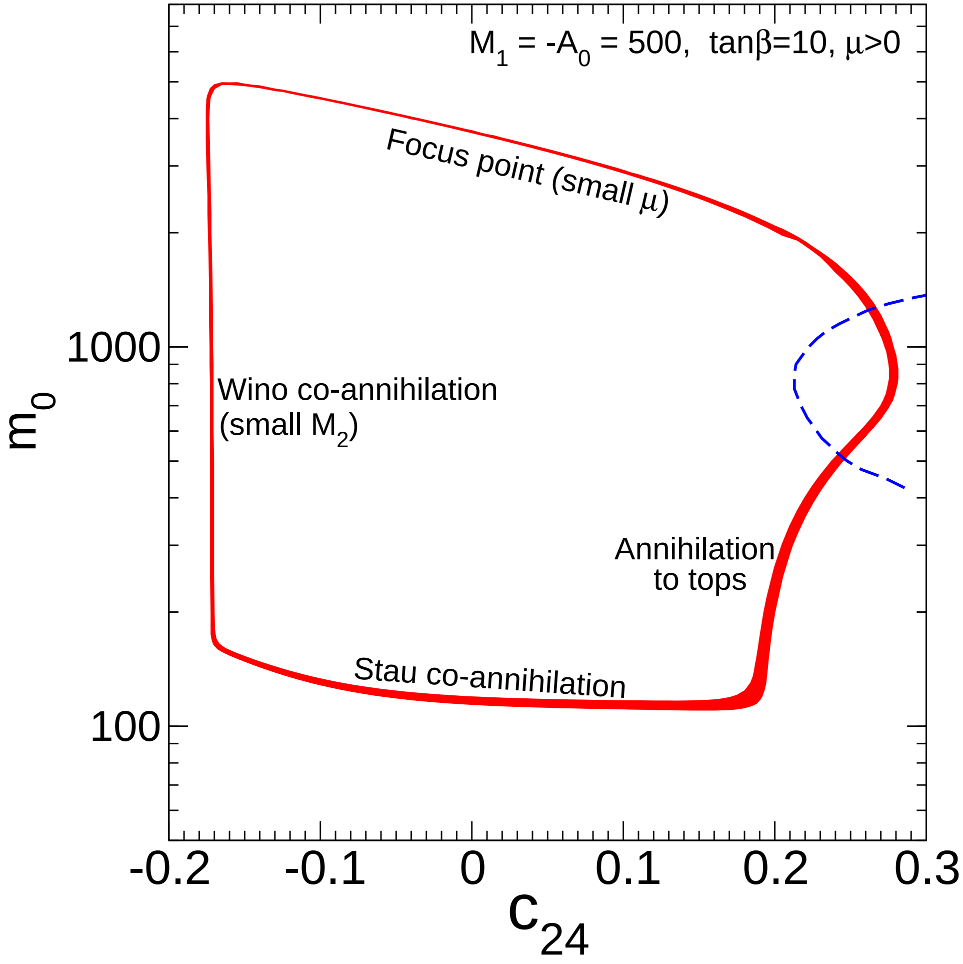
For $m_{1/2} = 500$ GeV, $m_0 = 150$ GeV, weak-scale parameters are:





“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.

Different dark matter allowed regions are continuously connected:

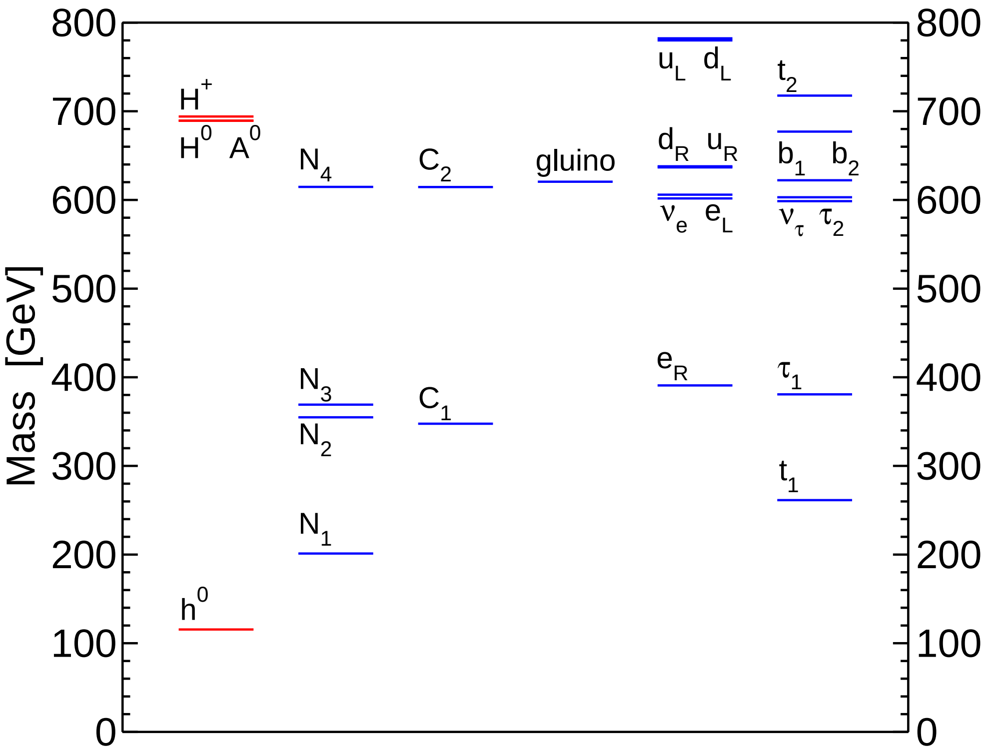


Red region is allowed by $\Omega_{\mathrm{CDM}}h^2 = 0.11 \pm 0.02$.

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:

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

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

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

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

Distinctive features of Compressed SUSY:

- Ratio of heaviest to lightest superpartner masses is < 4.
- $\tilde{t}_1$ is light, cannot decay to $t\tilde{N}_1$ in this scenario.
- Sleptons, charginos, and neutralinos other than LSP nearly decouple from LHC.

Compressed SUSY presents tough challenges:

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

The last point makes it very unlikely that we can “measure” the ratio $M_1 : M_2 : M_3$ at LHC.

An ILC with very high energy (> 1 TeV, at least) will be necessary.

Distinctive LHC signal:

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

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

$$\ell^+\ell^+bb + \text{jets} + \not{E}_T,$$
$$\ell^-\ell^-bb + \text{jets} + \not{E}_T$$

(See also Kraml and Raklev hep-ph/0512284 for the same SUSY signal in a different context.)

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

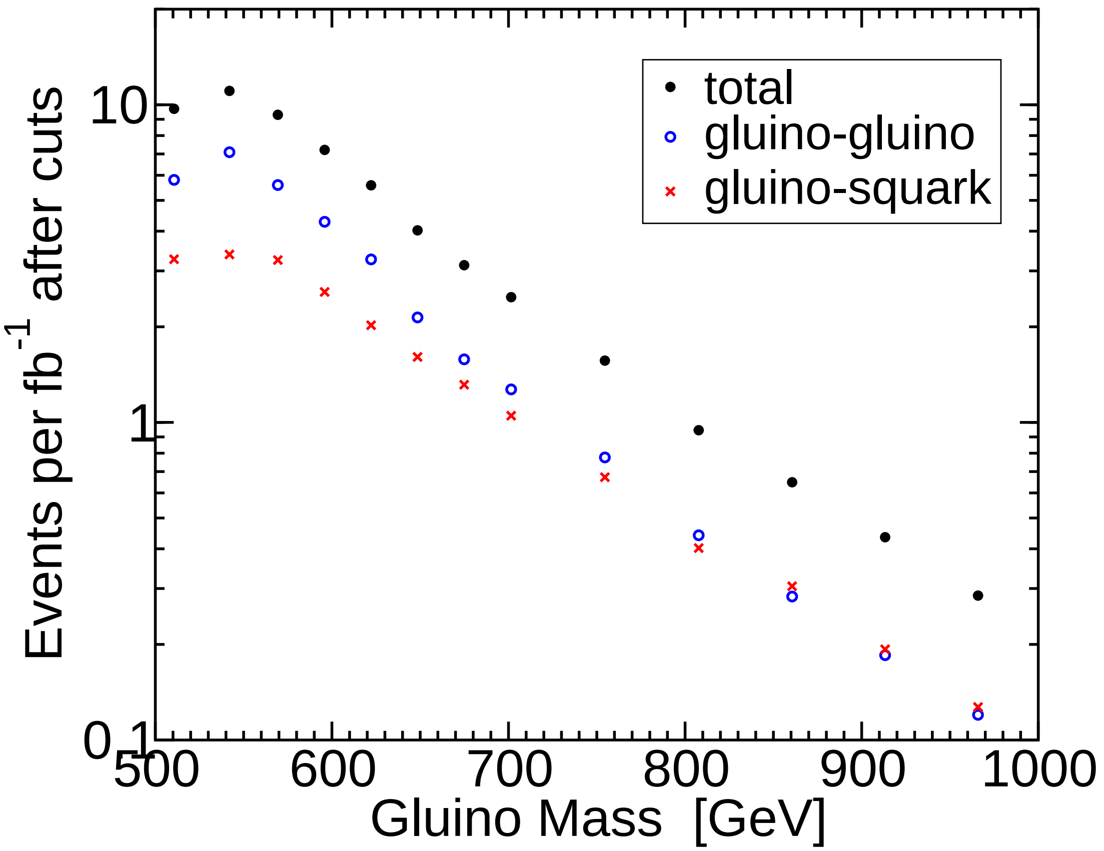
Use MadGraph/MadEvent $\longrightarrow$ Pythia $\longrightarrow$ PGS4 for event generation and detector simulation.

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
- $\not{E}_T > 100$ GeV

With these cuts, the Standard Model background is mostly $t\bar{t}$: less than 1 event/fb^{-1}. (Kraml and Raklev hep-ph/0512284.)

Signal rates, after cuts, for $\ell^{\pm}\ell^{\pm}bbjj + \not{E}_T$



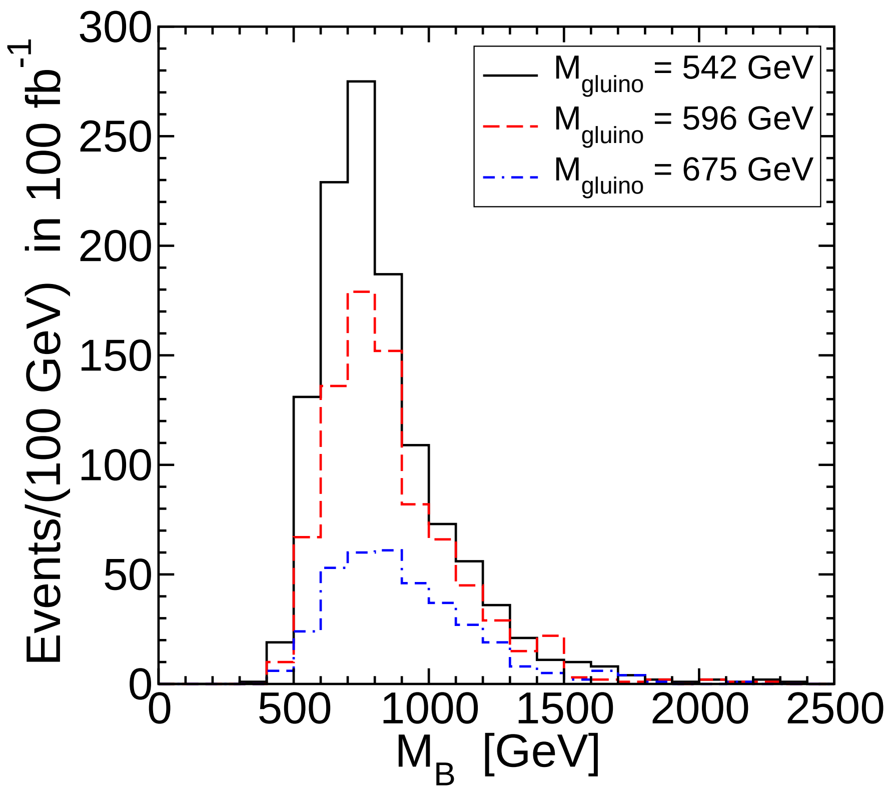
Detection prospects will depend on how well Same-Sign lepton backgrounds can be understood.

Consider a mass estimator (similar to M_{eff}):

$$M_B = \sum_{n=1,2,3,4} p_T(j_n) + \sum_{n=1,2} p_T(\ell_n) + E_T^{\mathrm{miss}}$$

Since the production is dominated by gluino-gluino and gluino-squark, this should be be correlated with the gluino mass.

Size and shape of the M_B distribution correlates with the gluino mass.

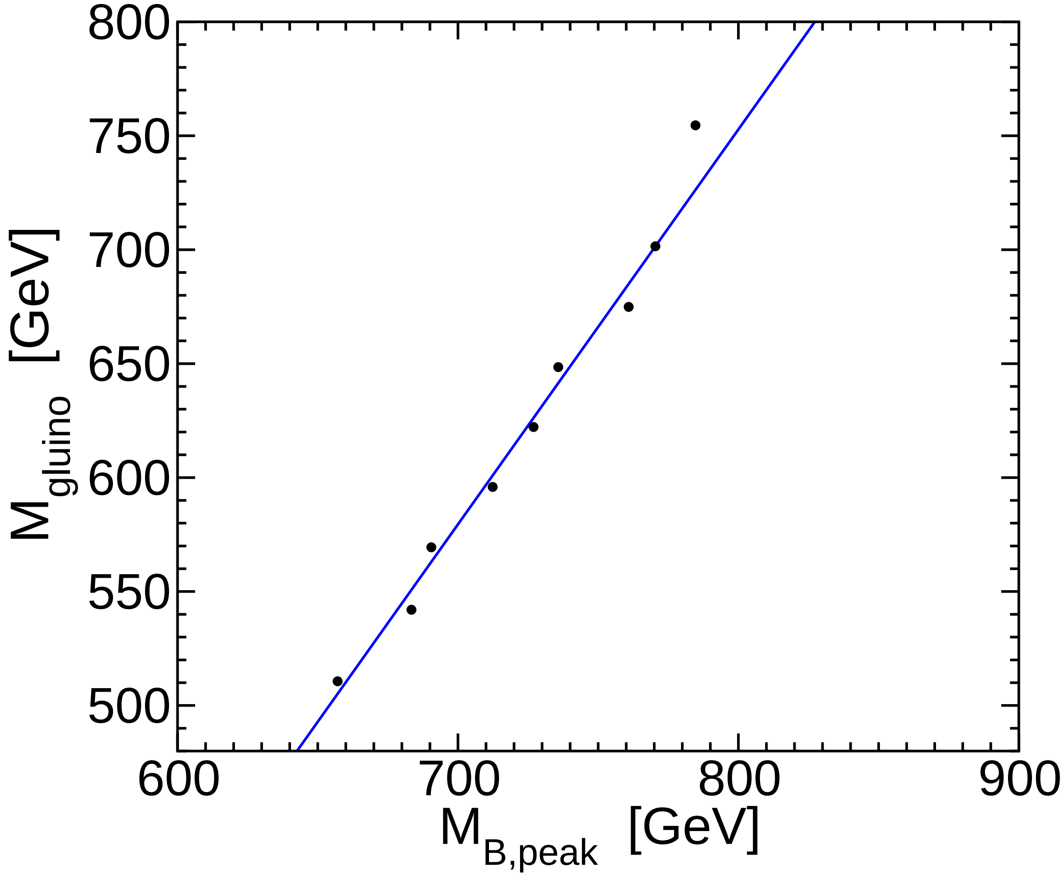


I find the shapes are fit well by generalized inverse Gaussian distributions with independent parameters a, b, c:

$$\frac{1}{\sigma}\frac{d\sigma}{dM_B} = \frac{1}{N}(M_B - M_B^{\text{min}})^{-c} \exp\left[-b\frac{(M_B - M_B^{\text{min}} - a)^2}{2(M_B - M_B^{\text{min}})}\right]$$

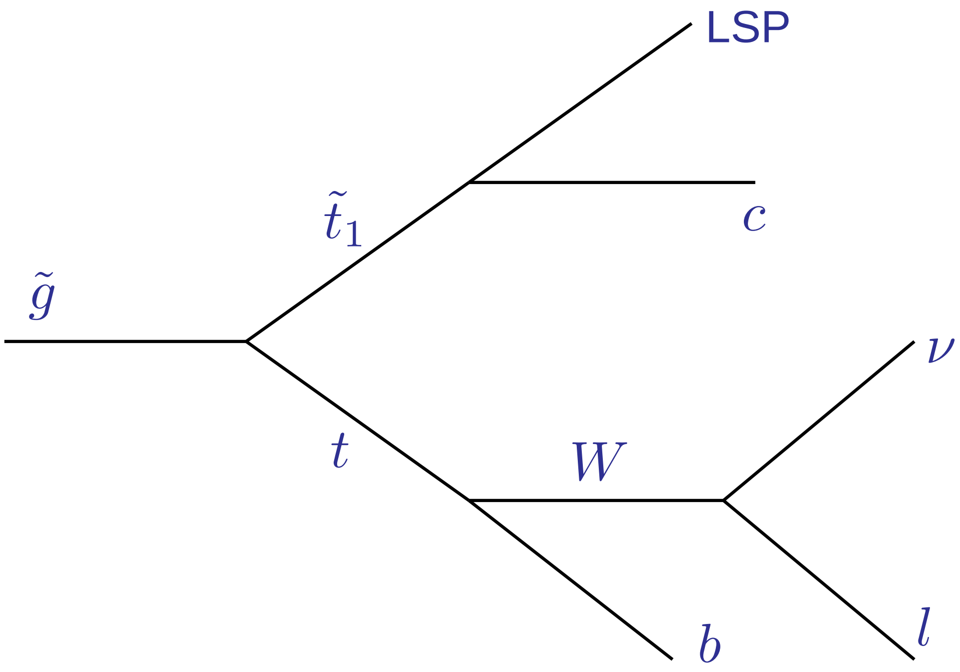
The fit value of c is usually very close to $3/2$; I don't know why.

From fits to 100 fb^{-1} of data for various gluino masses:



$$M_{\tilde{g}} \;=\; 1.73 M_{B,\,\text{peak}} - 630\,\text{GeV}$$

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



The top decay has:

$$M^2(bl)_{\max} \quad = \quad m_t^2 - m_W^2 \approx (153\,\mathrm{GeV})^2.$$

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:

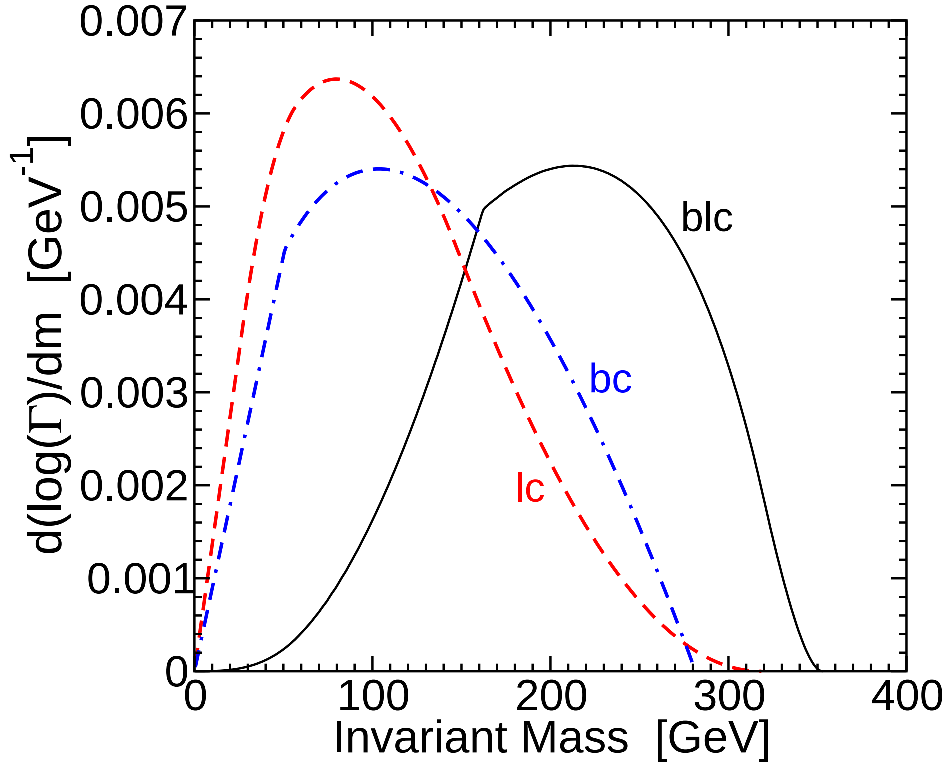
$$
\begin{aligned}
M^2(lc)_{\max} &= \frac{1}{2}\left(1-\frac{m^2_{\tilde{N}_1}}{m^2_{\tilde{t}_1}}\right)\left[m^2_{\tilde{g}}-m^2_{\tilde{t}_1}-m^2_t+\lambda^{1/2}(m^2_{\tilde{g}},m^2_{\tilde{t}_1},m^2_t)\right] \\
M^2(bc)_{\max} &= \left(1-\frac{m^2_W}{m^2_t}\right)M^2(lc)_{\max} \\
M^2(blc)_{\max}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

Here $\lambda(x,y,z)=x^2+y^2+z^2-2xy-2xz-2yz$.

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.

The theoretical shapes of the $M(lc)$, $M(bc)$, and $M(blc)$ distributions:



This is for $m_{\tilde{g}} = 596, \ \ m_{\tilde{t}_1} = 261,$ and $m_{\tilde{t}_1} = 201$ GeV.

Endpoints are $m(lc)_{\max} = 320, \ \ m(bc)_{\max} = 283, \ \ m(blc)_{\max} = 354$ GeV.

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

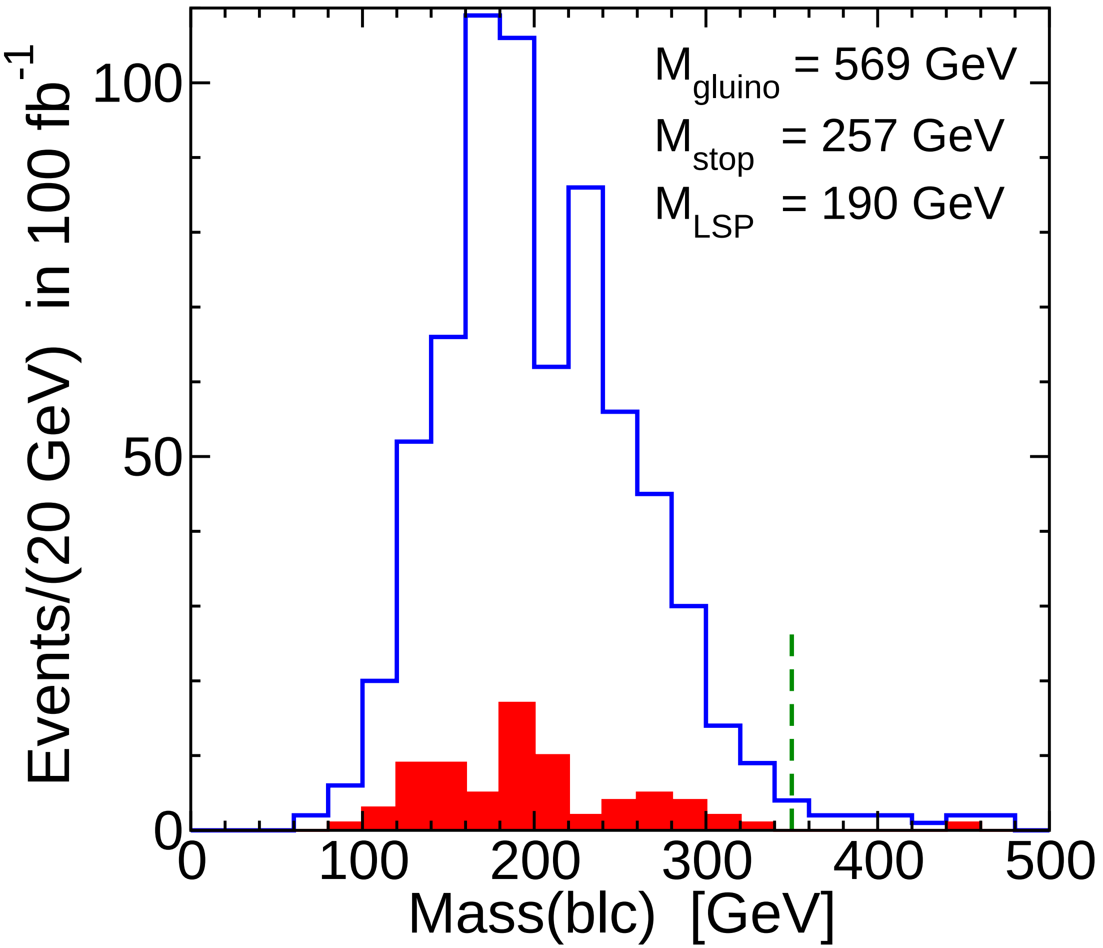
To get as clean a sample as possible:

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 jet candidate. Require $p_T(j_c) > 35$ GeV.

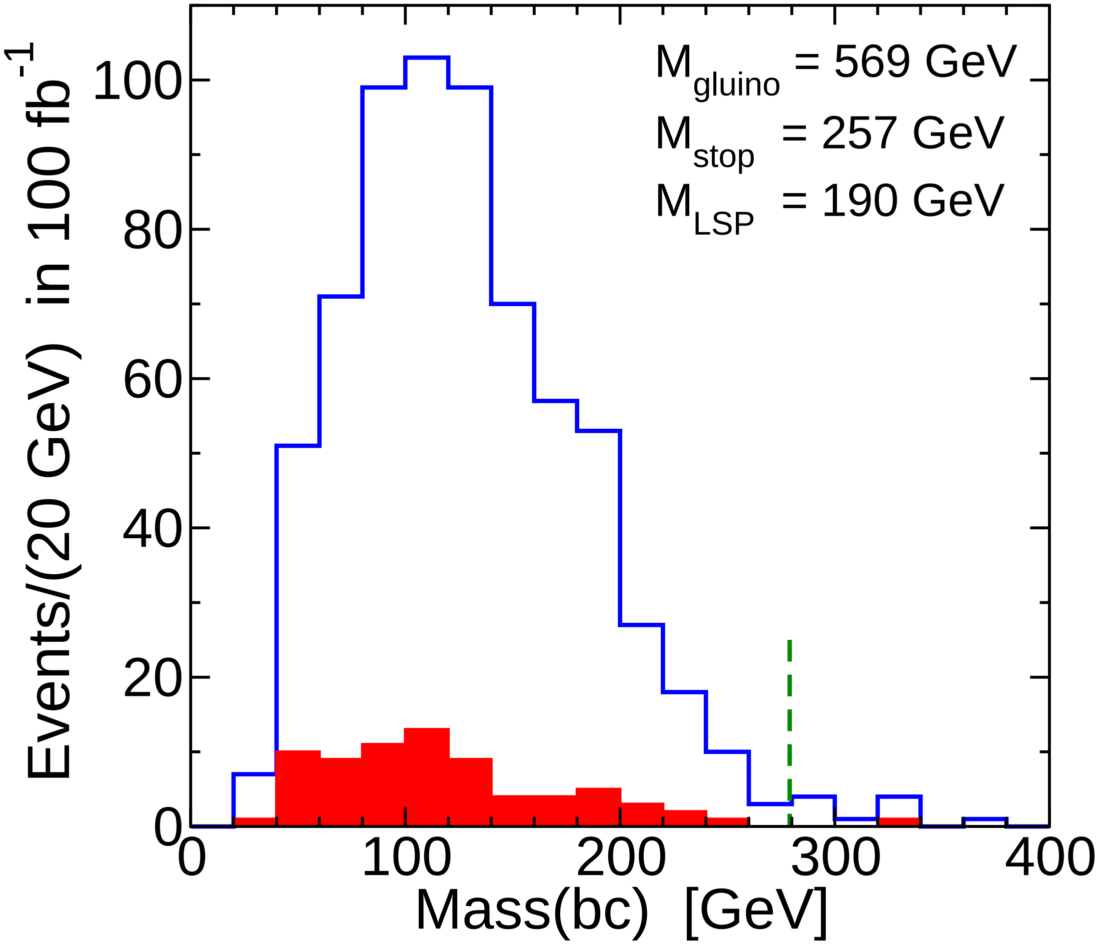
Look for the endpoints in both $M(blc)$ and $M(bc)$.

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

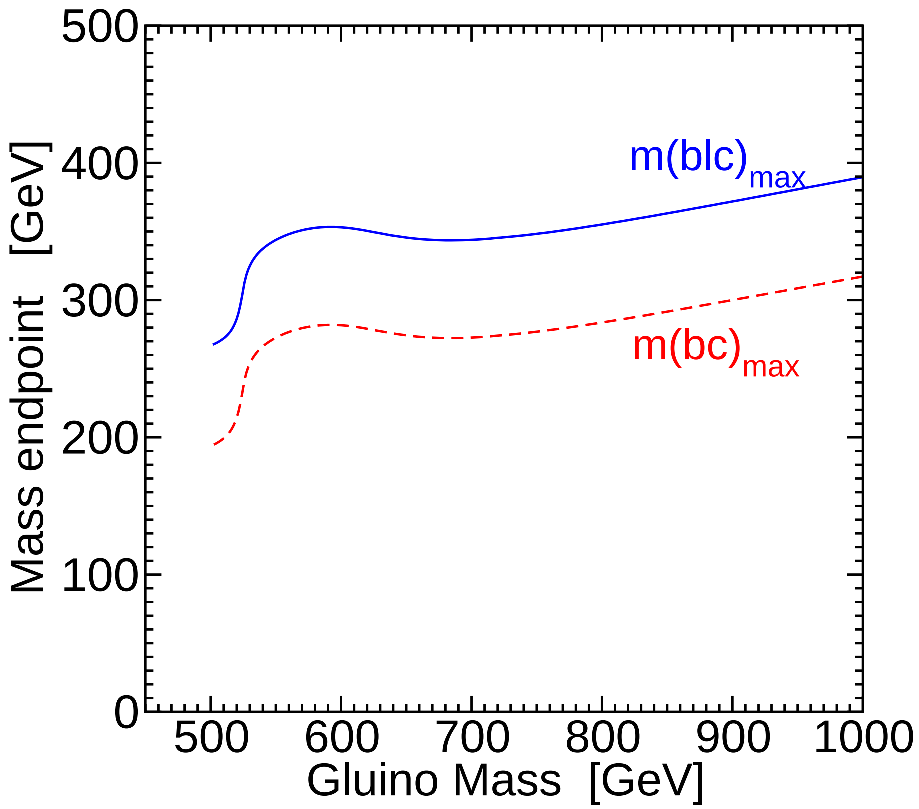


Red part = charm jet also has a heavy flavor tag or soft muon

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

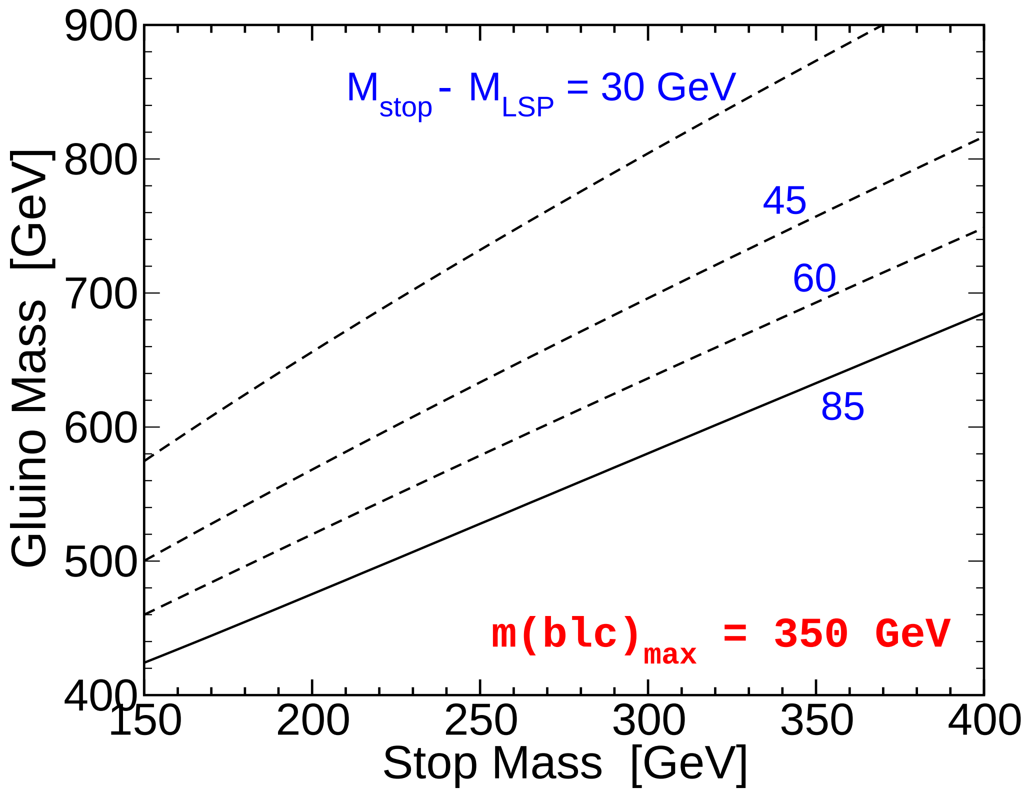


Now, the Bad News. In principle, the endpoints carry information about the gluino, top-squark and LSP masses. But in practice they depend only very weakly on the model!



So this will mostly provide confirming evidence of the signal’s origin, rather than definite information about the superpartner masses.

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

Cross-section measurement will put an upper limit on the gluino mass.

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

Conclusion

Gaugino masses from an F-term in a combination of a singlet of $SU(5)$ with some $\mathbf{24}$ of SU(5) or $\mathbf{54}$ of SO(10) has distinctive features, including stop-mediated annihilation of dark matter to $t\bar{t}$ in the early universe.

However, it will likely not be fully distinguishable at the LHC.

An ILC will need a very high energy to sort things out, if this scenario turns out to be correct.

Stoponium at the LHC is an interesting long-term signal. For more, go to James Younkin's talk in the Top Sector session on Tuesday afternoon.