Squashed† supersymmetry at the LHC

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Workshop on Searches for Supersymmetry at the LHC

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`1105.4304` with Tom LeCompte, based on 2010 data, updated here to now reflect 2011 search signal regions reported by ATLAS in 1109.6572 (1.04 fb^{-1}).

† also known as: compressed, squished, squeezed, crunched, scrunched, compacted. . .

What happens if the superpartner mass spectrum is more compressed?

Less visible energy: smaller jet p_T's, $m_{\rm eff}$ or H_T, and $E_T^{\rm miss}$.

Signal looks more like QCD, $t\bar{t}$, W+jets, and Z+jets backgrounds.

Radiation of additional QCD jets is important; supplies transverse kick. (Alwall, de Visscher, Maltoni 0810.5350; Alwall, Le, Lisanti, Wacker 0809.3264; Alves, Izaguirre, Wacker 1102.5338.)

Motivation 1: the LHC vs. SUSY Models, 2010/2011

Motivation 2: the SUSY little hierarchy problem

Electroweak symmetry breaking seems to imply a percent-level fine-tuning:

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

Less fine-tuning if $|m_{H_u}^2|$ and $|\mu|^2$ are small.

Claim: this points to a more compressed superpartner mass spectrum.

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)

$$
\begin{aligned}
-m_{H_u}^2 \quad = \quad & 1.92 M_3^2 + 0.16 M_2 M_3 - 0.21 M_2^2 \\
& -0.63 m_{H_u}^2 + 0.36 m_{t_L}^2 + 0.28 m_{t_R}^2 \\
& + \text{many terms with small coefficients}
\end{aligned}
$$

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.

For example, one can parametrize:

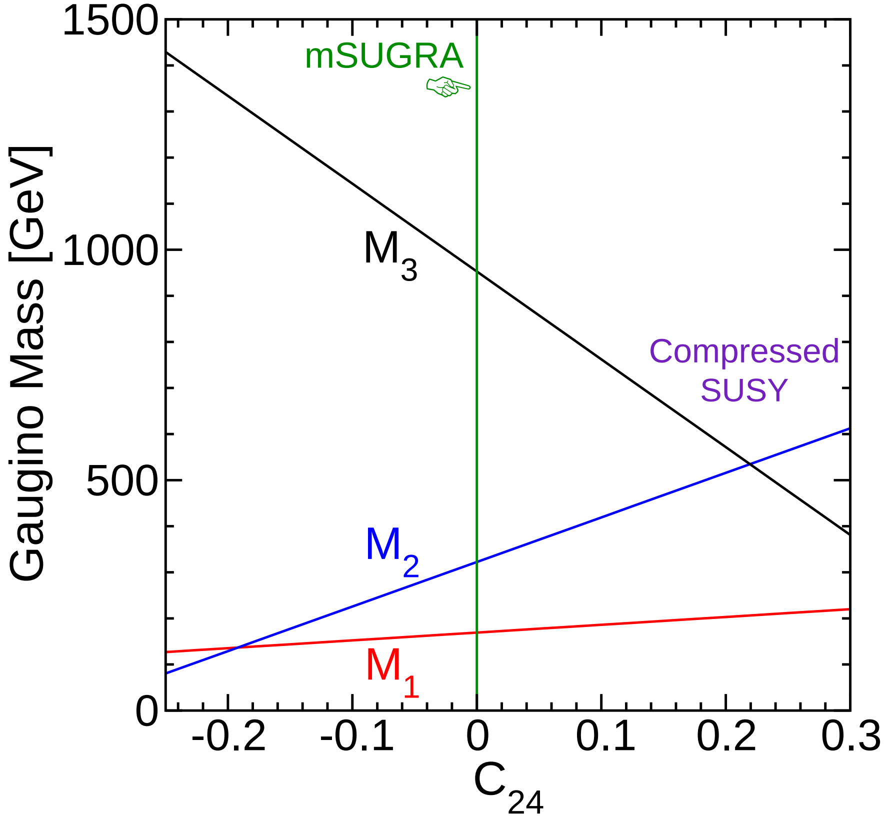
$$
\begin{aligned}
M_1 &= m_{1/2}(1 + C_{24}), \\
M_2 &= m_{1/2}(1 + 3C_{24}), \\
M_3 &= m_{1/2}(1 - 2C_{24}).
\end{aligned}
$$

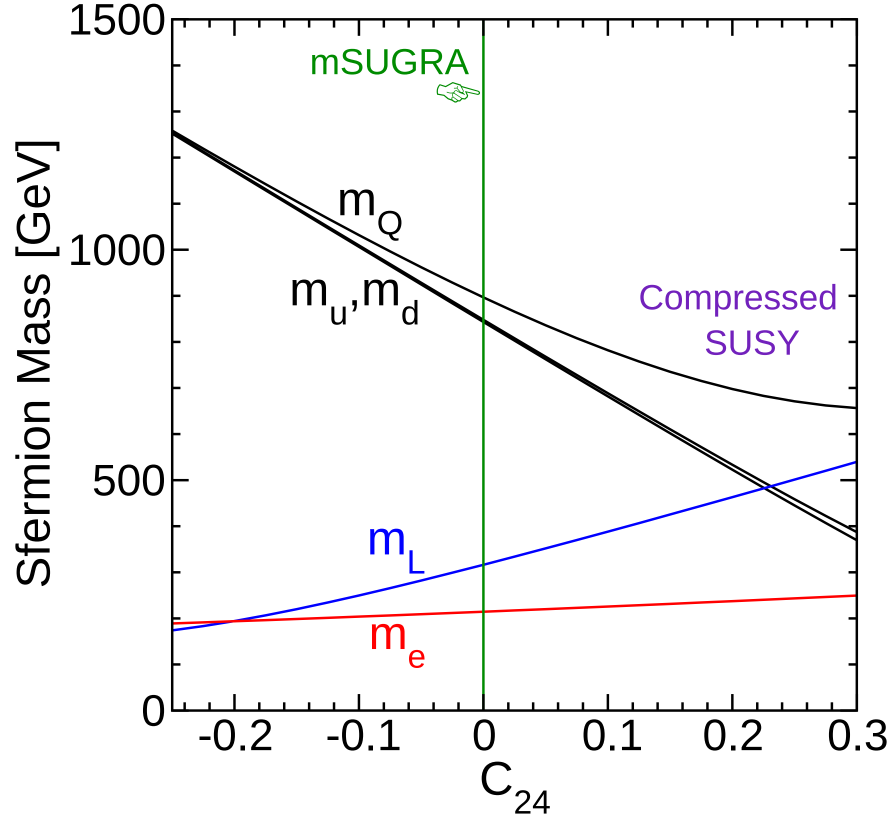
if the F terms that break SUSY include both a singlet and a $\mathbf{24}$ of $SU(5)$ or a $\mathbf{54}$ of $SO(10)$.

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

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

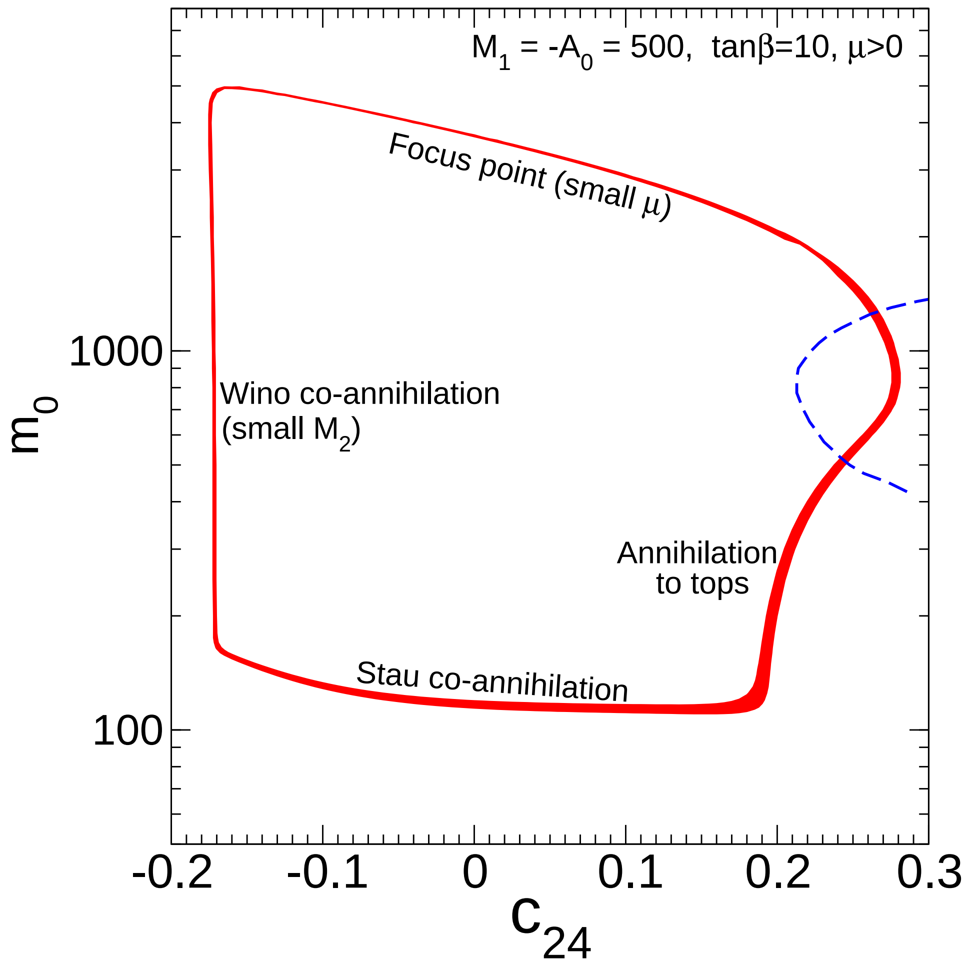
For $m_{1/2} = 500$ GeV, $m_0 = 150$ GeV, weak-scale parameters are:





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

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.

For study: consider models that generalize mSUGRA by including a "compression factor" c. At the TeV scale:

$$M_1 = \left(\frac{1+5c}{6}\right) M_{\tilde{g}}, \qquad M_2 = \left(\frac{1+2c}{3}\right) M_{\tilde{g}},$$

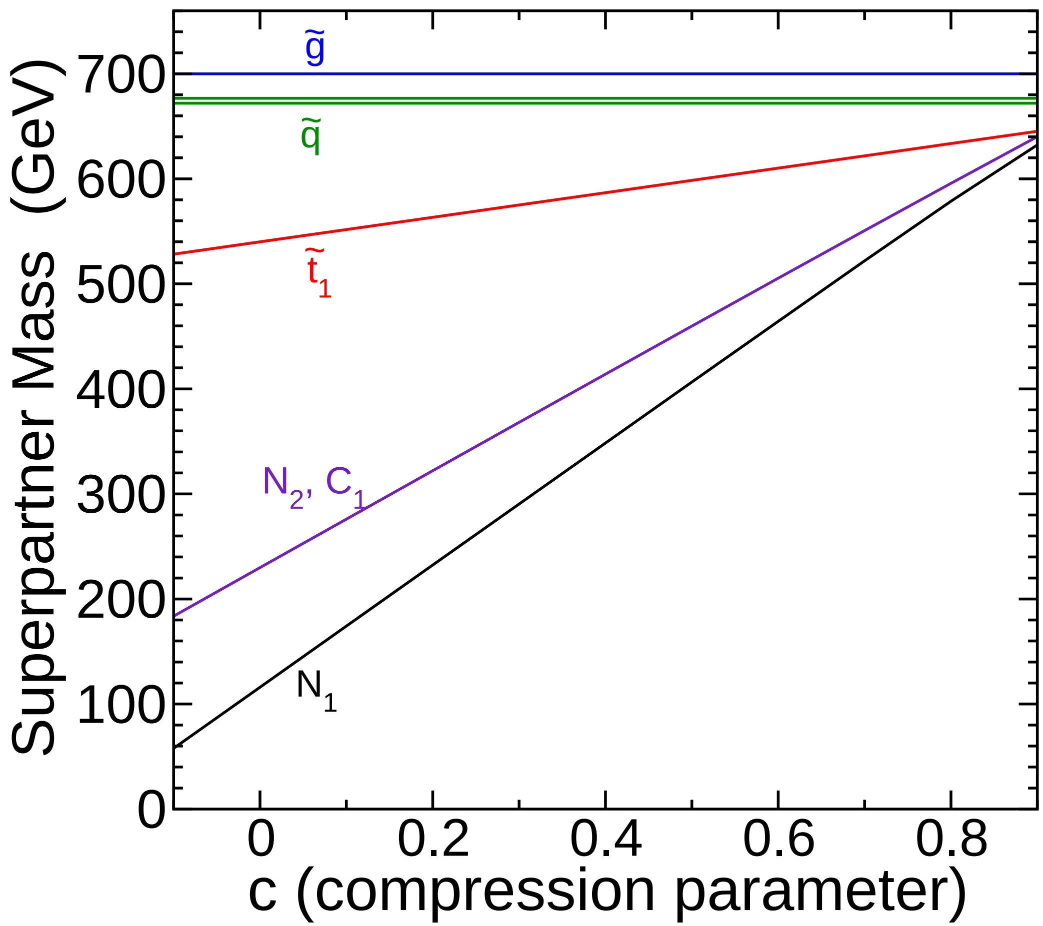
- $c = 0$ corresponds to mSUGRA.
- $c = 1$ is total compression (gauginos degenerate).

Also take $\tan\beta = 10$, $\mu > 0$, and squark masses

$$M_{\tilde{Q}} = 0.96 M_{\tilde{g}}.$$

Variable input parameters: $M_{\tilde{g}}$ (overall superpartner mass scale) and c (compression factor).

Masses of important superpartners, as a function of c, for $M_{\tilde{g}} = 700$ GeV:



Use ATLAS cuts from Summer 2011 (EPS) data analyses, including:

	A	B	C	D	E
number of jets	≥ 2	≥ 3	≥ 4	≥ 4	≥ 4
$p_T(j_1)$ [GeV]	> 130	> 130	> 130	> 130	> 130
$p_T(j_n)$ [GeV]	> 40	> 40	> 40	> 40	> 80
$m_{\rm eff}$ [GeV]	> 1000	> 1000	> 500	> 1000	$> 1100^{\dagger}$
$E_T^{\rm miss}/m_{\rm eff}$	> 0.3	> 0.25	> 0.25	> 0.25	> 0.2
1.04 fb^{-1} limit	$<$ 22 fb	$<$ 25 fb	$<$ 429 fb	$<$ 27 fb	$<$ 17 fb

ATLAS 1109.6572

† inclusive $m_{\rm eff}$: sum jets with $p_T > 40$

Limits are 95% CL on cross-section times acceptance.

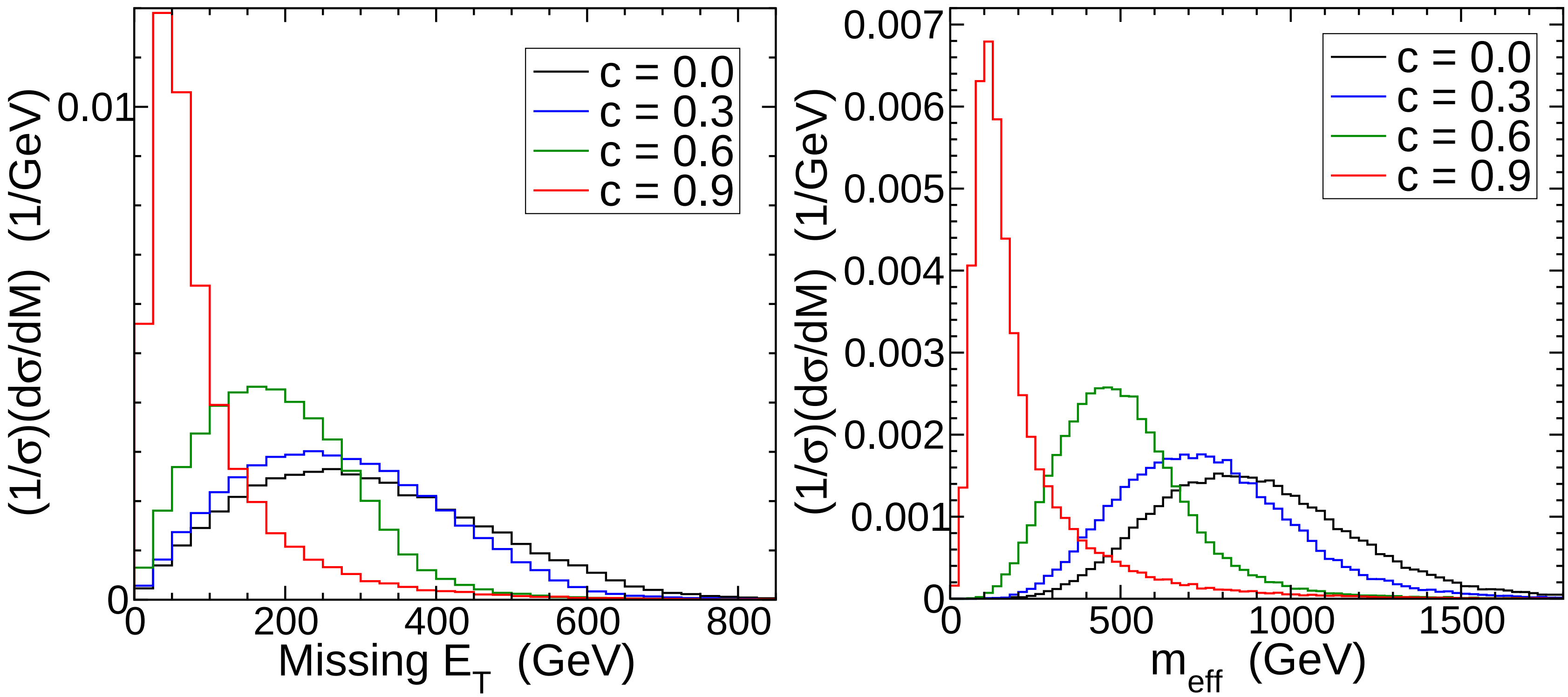
Used MadGraph/MadEvent to generate hard scattering events, Pythia for decays and showering and hadronization, PGS4 for detector simulation.

Matrix element and shower/hadronization jet matching done with MLM method by including 1 extra jet at matrix element level for each signal process.

This is potentially important when the mass spectrum is compressed, but with our setup we found it didn't make a huge difference.

Cross-sections for $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{Q}$, $\tilde{g}\tilde{Q}^*$, $\tilde{Q}\tilde{Q}$, $\tilde{Q}\tilde{Q}^*$, $\tilde{Q}^*\tilde{Q}^*$, $\tilde{t}_i\tilde{t}_i^*$, $\tilde{b}_i\tilde{b}_i^*$, normalized to Prospino.

$E_T^{\rm miss}$, $m_{\rm eff}$ distributions for $M_{\tilde{g}} = 700$ GeV, and $c = 0.0$, 0.3, 0.6, 0.9.

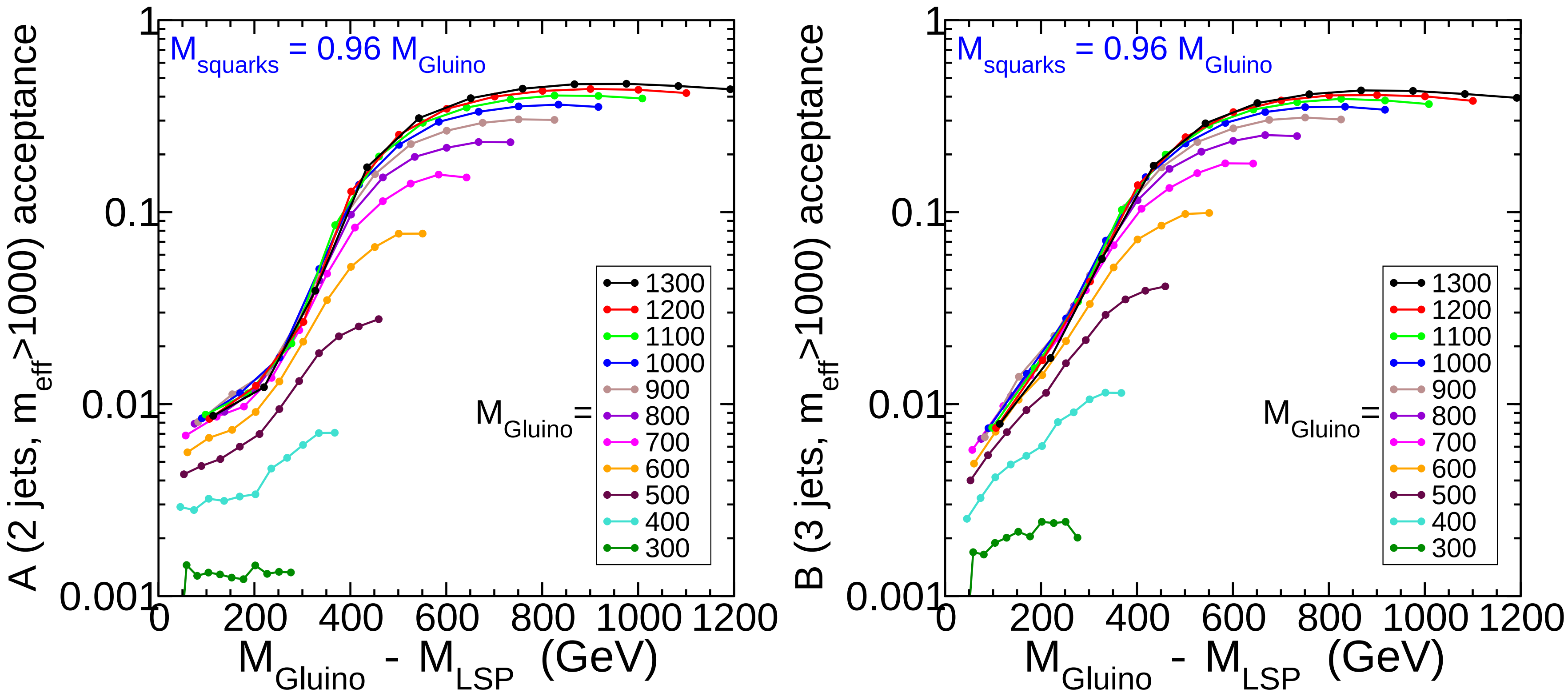


As c increases, $m_{\rm eff}$ gets soft faster than $E_T^{\rm miss}$ does.

For moderate compression, acceptance can even increase with c; more events pass $E_T^{\rm miss}/m_{\rm eff} >$ cuts.

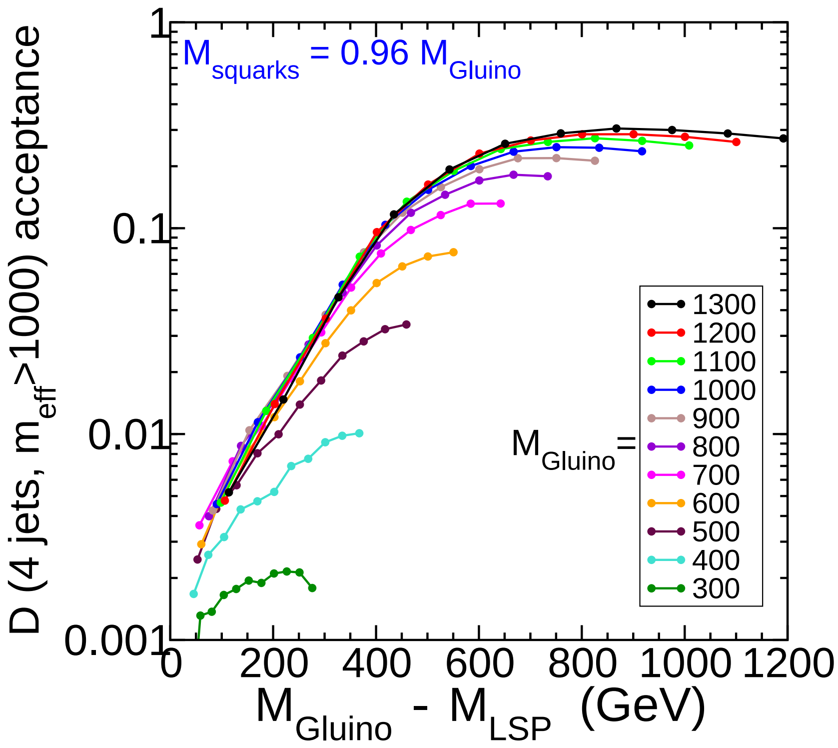
Distributions become very soft at high compression c.

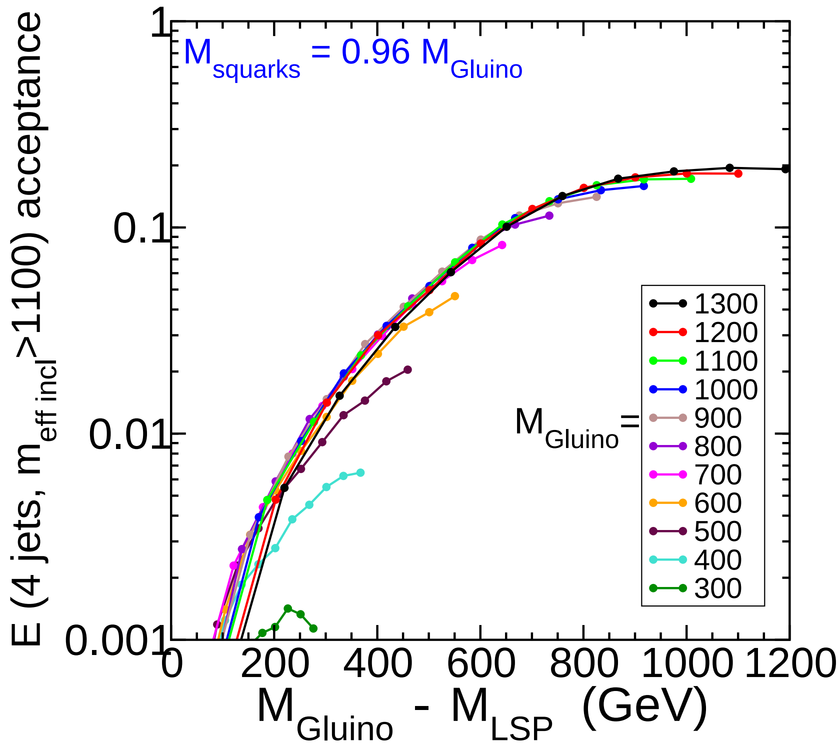
A and B acceptances for $M_{\tilde{g}} = 300, 400, 500, \ldots 1300$ GeV:



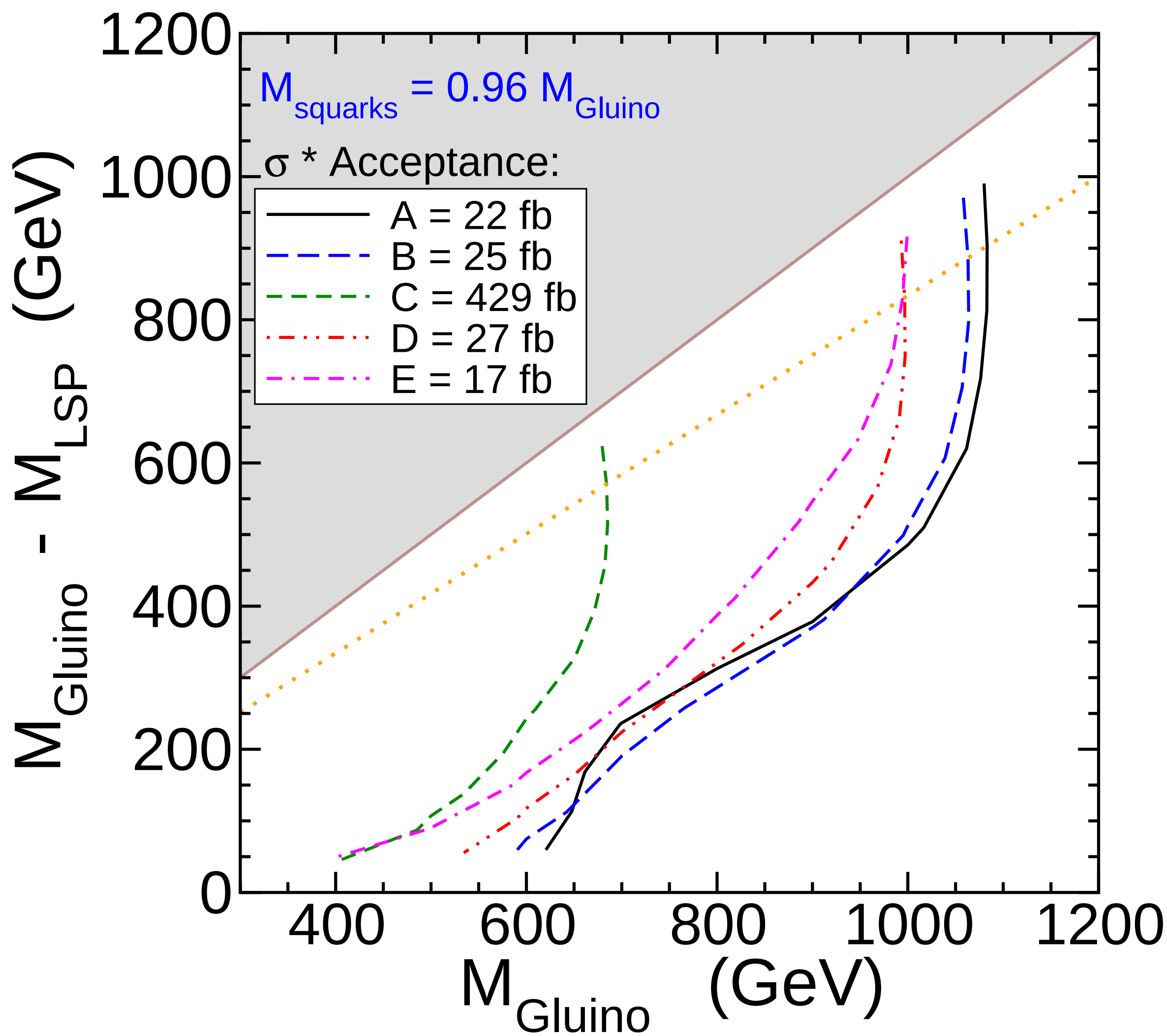
Dots on each line are at $c = -0.1,\ 0,\ 0.1,\ \ldots,\ 0.9$ from right to left.

D and E acceptances are somewhat worse for this class of models, especially at extreme compression:

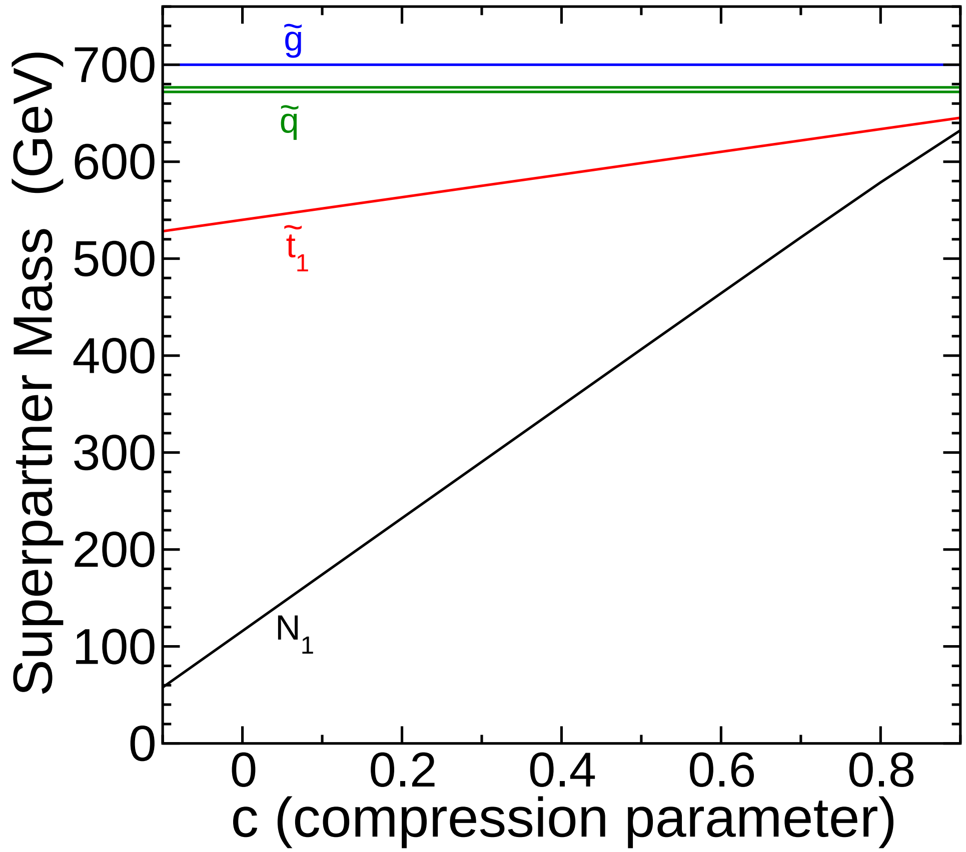




$\sigma \times$ Acceptance contours, corresponding to the ATLAS 1.04 fb^{-1} limits reported in 1109.6572:

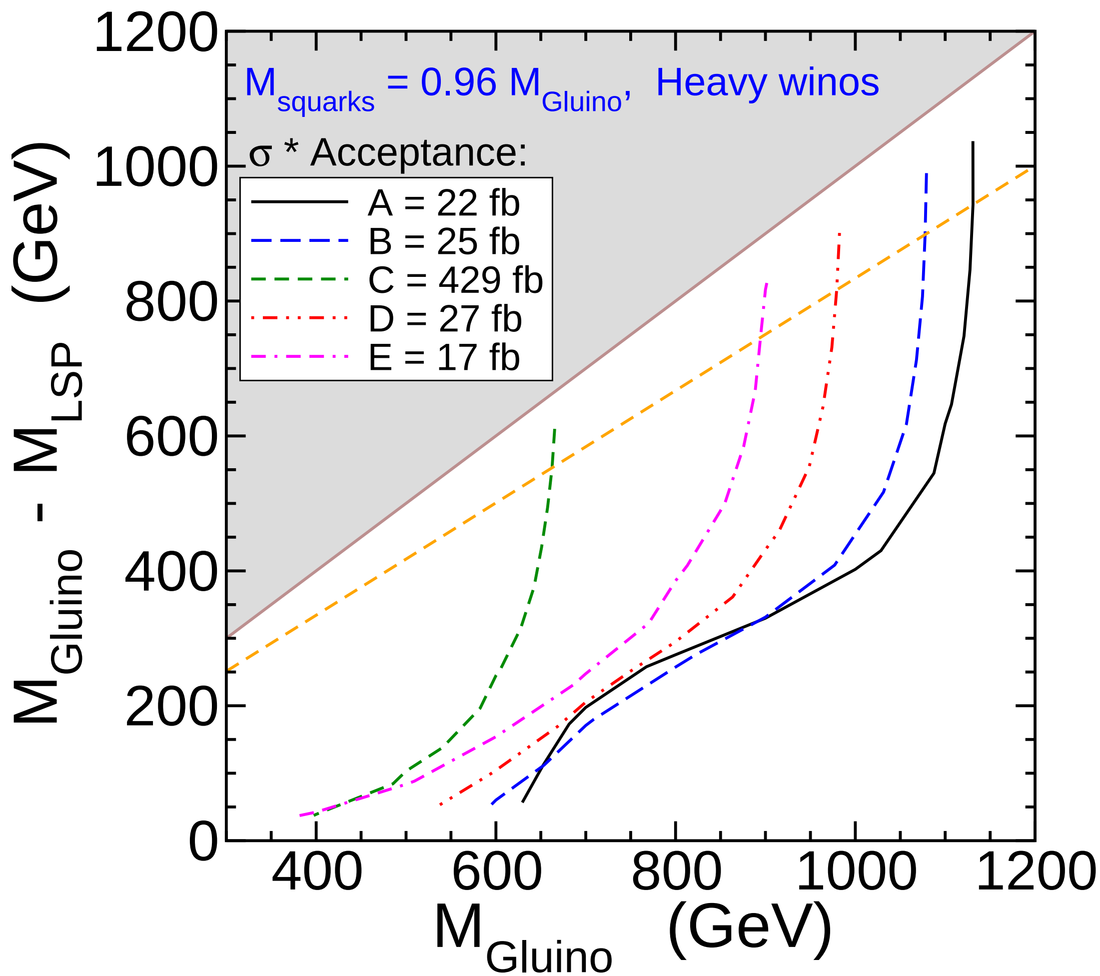


Now consider a modified model in which the winos are taken much heavier, spectrum otherwise the same:



This gives a stronger signal, because visible energy is shared among fewer jets. Note $\tilde{g} \to t\tilde{t}_1$ is kinematically forbidden.

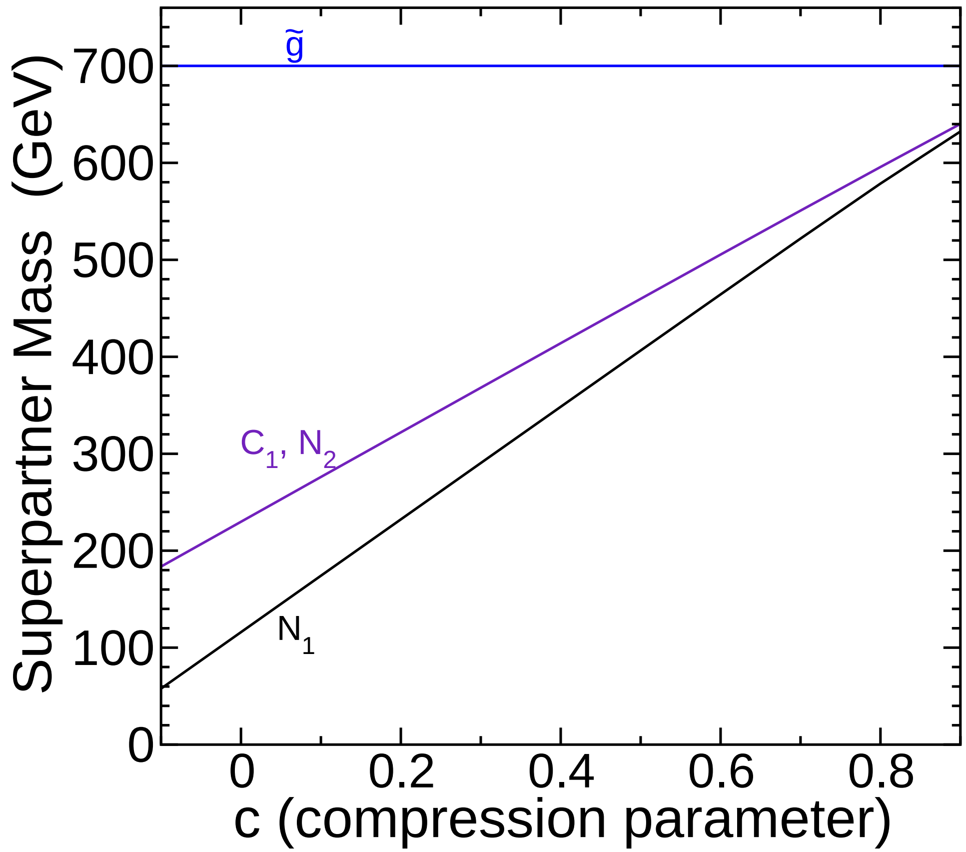
$\sigma\times$ Acceptance contours corresponding to the ATLAS 2011 1.04 fb^{-1} limits, for Heavy Wino models:



Limits slightly stronger, still down to nearly $M_{\tilde{g}} = 600$ for $c = 1$.

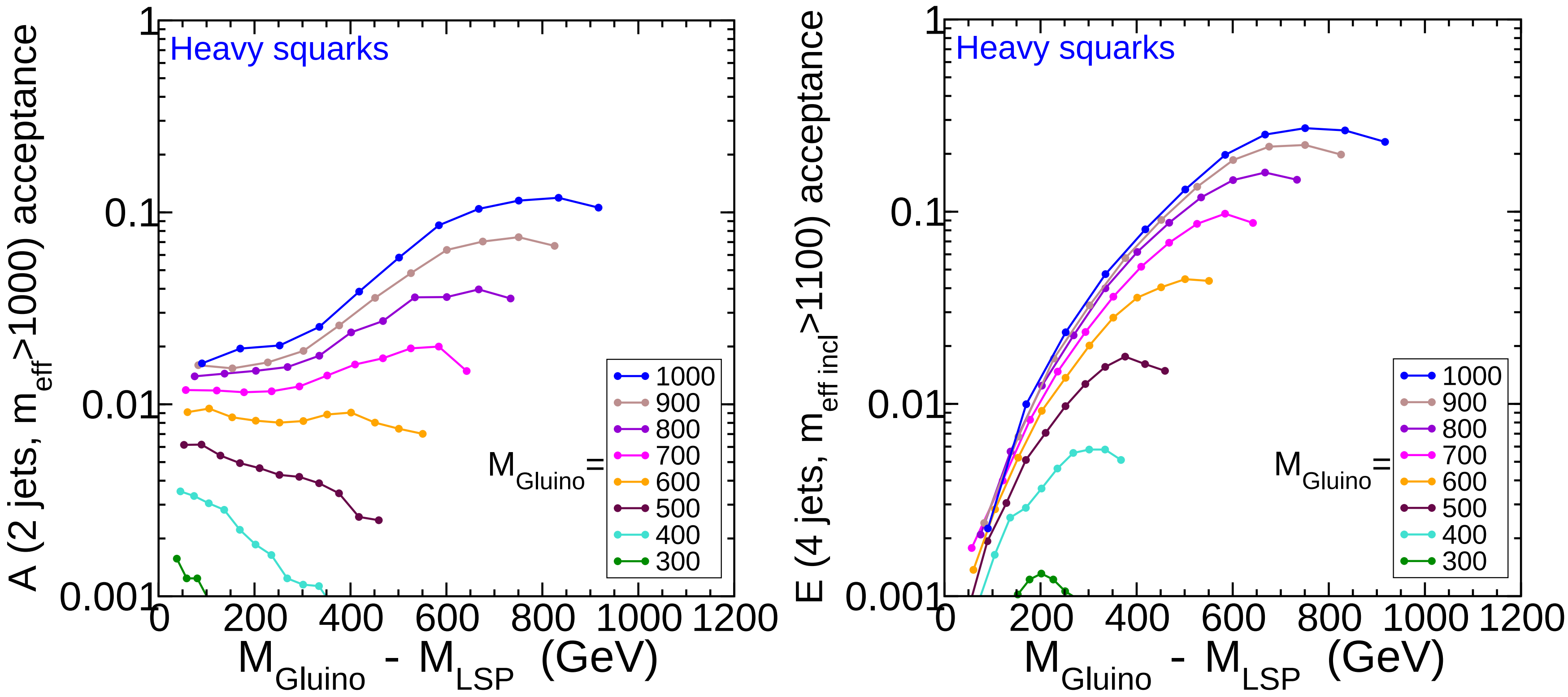
What if squarks are much heavier?

Consider variable $M_{\tilde{g}}$ and compression parameter c as before, but now take squarks out of the picture: $M_{\tilde{Q}} = M_{\tilde{g}} + 1000\ \mathrm{GeV}$.

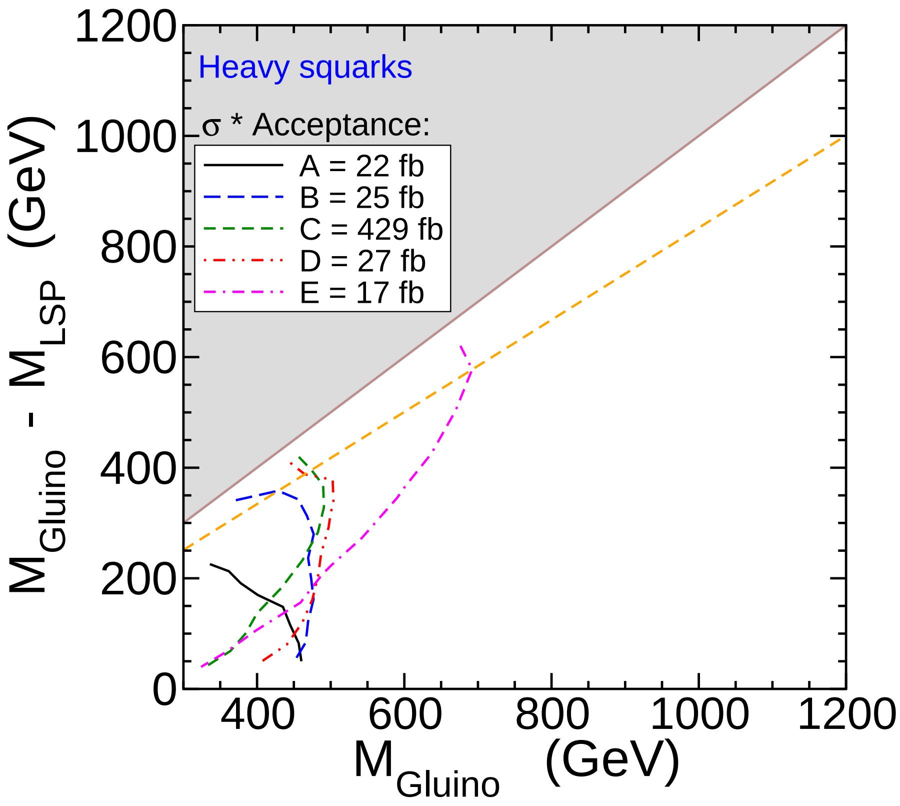


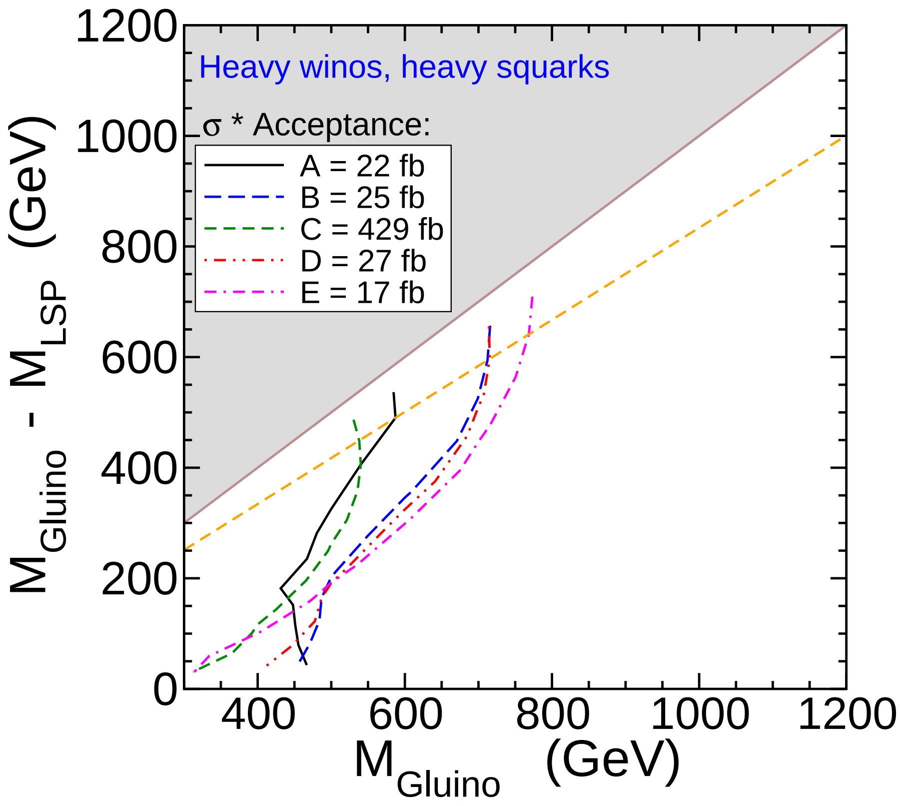
Now $\tilde{g} \to jj\tilde{W} \to jjjj + E_T^{\mathrm{miss}}$ dominates.

For low compression, signal E (4 jets, inclusive $m_{\rm eff}$) wins, but as the compression increases, B (3 jets) and then A (2 jets) take over.



$\sigma \times$ Acceptance contours corresponding to the ATLAS 2011 1.04 fb^{-1} limits, for Heavy Squark models:





What to do?

ATLAS defines:

$$m_{\text{eff}} = E_T^{\text{miss}} + \sum_{i=1}^{n} p_T(j_n)$$

where $n =$ the number of jets required by the signal (except for signal E).

For more compression of masses, m_{eff} gets soft faster than E_T^{miss} does. A high m_{eff} cut is deadly unless one includes many (≥ 4) jets.

But, with compressed SUSY, requiring 4 hard jets also kills the signal.

Suggestions:

- Require fewer jets (or lower p_T threshold for subleading jets), but sum over more of them in defining $m_{\rm eff}$,

  AND/OR

- Choose lower cut on $m_{\rm eff}$ (750 GeV?), and a higher cut on $E_T^{\rm miss}/m_{\rm eff}$ (0.35?) to compensate.
- Collect more data and be patient...

Non-sequitur: some personal remarks and suggestions on LHC SUSY searches in general.

Model dependence is inevitable.

Both mSUGRA/CMSSM and simplified model limits are useful. However. . .

1) Please **do** provide information (SLHA model files or full model definitions, acceptance$*$efficiency, expected number of events in search data sample) on all individual grid model points used in setting limits!

Nice example: Figures 16-20, ATLAS 2010 search page

`https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2010-05/`

This allows estimates, and checks, of search reaches for other models. Pretty color-coded grids are nice, but actual numbers are better.

2) Consider mSUGRA models with larger $\tan\beta$ and $|A_0|$, not just 10 and 0.

One often sees the claim that such models will produce similar limits to the ones already considered. However, this may not be completely robust.

In any case, models with $A_0 = 0$ were often ruled out already in the last century by Higgs searches at LEP.

3) In mSUGRA searches, whenever a m_0 vs. $m_{1/2}$ plane is shown, please also provide the same exclusion limits in the $M_{\tilde{g}}$ vs. $M_{\tilde{Q}}$ plane.

Grids of squark and gluino masses are typically superimposed on m_0 vs. $m_{1/2}$ plots, but are hard to decipher.

Physical masses are often more directly useful than model input parameters.

4) Take seriously the very large m_0 region (including the “focus point” or “hyperbolic branch”).

With $\gg 1$ fb^{-1}, these regions should be accessible.

They are not just extrapolations of somewhat smaller m_0; can have different branching ratios, qualitatively distinct.

5) Searches **requiring** $\geq 3\ b$ tags.

Should cut down on QCD, W+jets, Z+jets, and even $t\bar{t}$ backgrounds.

Can relax H_T, $m_{\rm eff}$, and $E_T^{\rm miss}$ cuts.

Many SUSY models (not necessarily prevalent in canonical mSUGRA searches) can have nearly all SUSY events with 4 or more b-taggable jets.

6) Do define kinematic variables precisely and explicitly in each conference talk and publication!

$m_{\rm eff}$, H_T, etc. often have slightly different definitions depending on the analysis.

In at least one case, the public analysis preprint is directly misleading about the definition of $m_{\rm eff}$ that was actually used.

7) Discovery sometime soon, please.

A hint, at least?

Outlook

- With mild to moderate compression, acceptances are not bad, and sometimes even better than mSUGRA.
- Acceptances do drastically decrease for more severe compression. (Even more dramatic for 1-lepton signal, and 6-8 jet signals, not shown here.)
- Compressed SUSY might contribute to QCD background control regions (used to estimate backgrounds from data) in a more significant way than in mSUGRA (?)
- Try lower $m_{\rm eff}$ cut, including more jets but requiring fewer, and higher $E_T^{\rm miss}/m_{\rm eff}$ cut?