Light stops

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Outline

- Motivations
  - Why some theorists think stops might be heavy
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- Varieties of stop decays
- Difficult and easy cases
- A comment on mSUGRA searches

Why theorists think stops might be heavy:

In MSSM, $M_h > 114$ GeV, and maybe $M_h \approx 125$ GeV.

$$M_h^2 = M_Z^2 \cos^2(2\beta) + \frac{3y_t^2}{4\pi^2} m_t^2 \sin^2\beta \left\{ \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + f_1 \sin^2(2\theta_{\tilde{t}}) - f_2 \sin^4(2\theta_{\tilde{t}}) \right\}$$

To get $M_h = 125$ in the MSSM, need:

- $\tan\beta \gtrsim 4$, AND
- heavy top squarks, OR
- large stop mixing

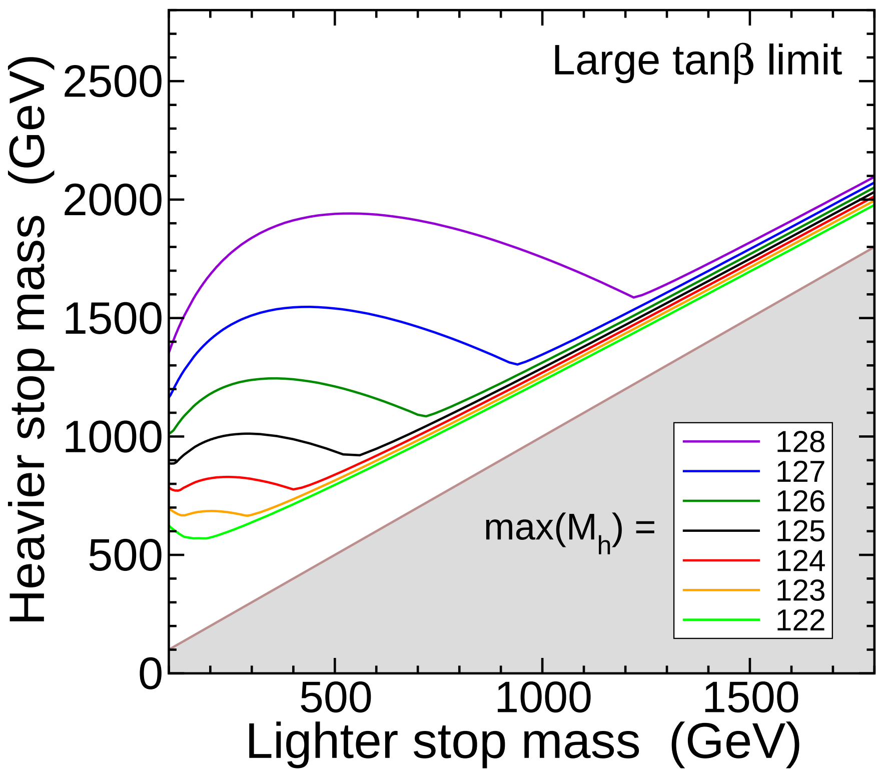
The maximum of $\Big\{\Big\}$, when varying $\theta_{\tilde{t}}$, has:

$$\Big\{\Big\} \longrightarrow \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + 3.$$

This is the "M_h-max" case. Stops can be light.

Consider general MSSM, no mSUGRA assumption. Top squark masses uncorrelated with other superpartner masses, mixing can be large.

For each $\tilde{t}_1$, $\tilde{t}_2$ masses, scan over other parameters, find maximum M_h:



Note: the version of this figure that was shown in the original version of this talk imposed a constraint from $\sigma \cdot BR(h \to \gamma\gamma)$ incorrectly. Thanks to Carlos Wagner for pointing this out. Corrected version is at left.

Otherwise, heavier top squark lighter than 700 GeV is feasible.

Why theorists think stops (and higgsinos and gluino) should be light:

Electroweak symmetry breaking gives

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

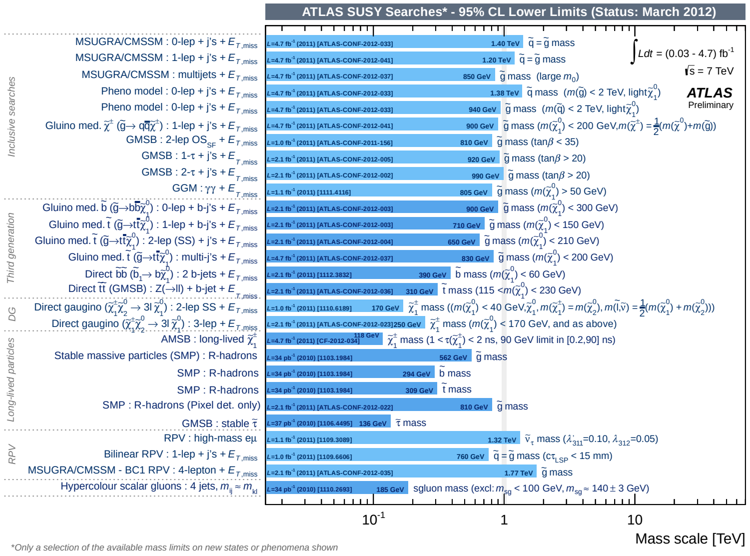
In terms of input parameters at GUT scale:

$$|m_{H_u}^2| = 1.92M_3^2 - 0.63m_{H_u}^2 + 0.36m_{\tilde{t}_L}^2 + 0.28m_{\tilde{t}_R}^2$$
$$+\text{many smaller terms}$$

This should be not far above M_Z^2 for small fine tuning.

Heavier gluino, Higgsinos, top squarks = more fine tuning.

Why theorists should be humble: LHC vs. SUSY models, 2012



Impact on fine-tuning?

Not much we can do about the gluino; most of the sensitive negative searches are based on it. We're stuck with some tuning.

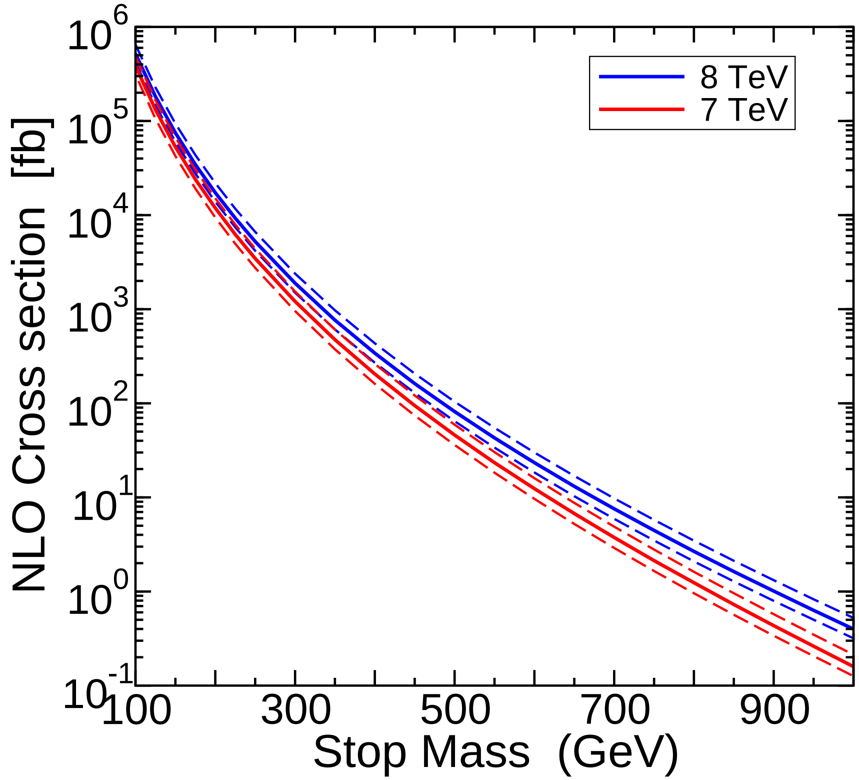
But we can still hope that $|\mu|$ is small, implying light Higgsinos, and that stops are light.

Even lighter top squarks are possible in **non-minimal** SUSY.

Two good, easy ways to raise the Higgs mass to 125 GeV:

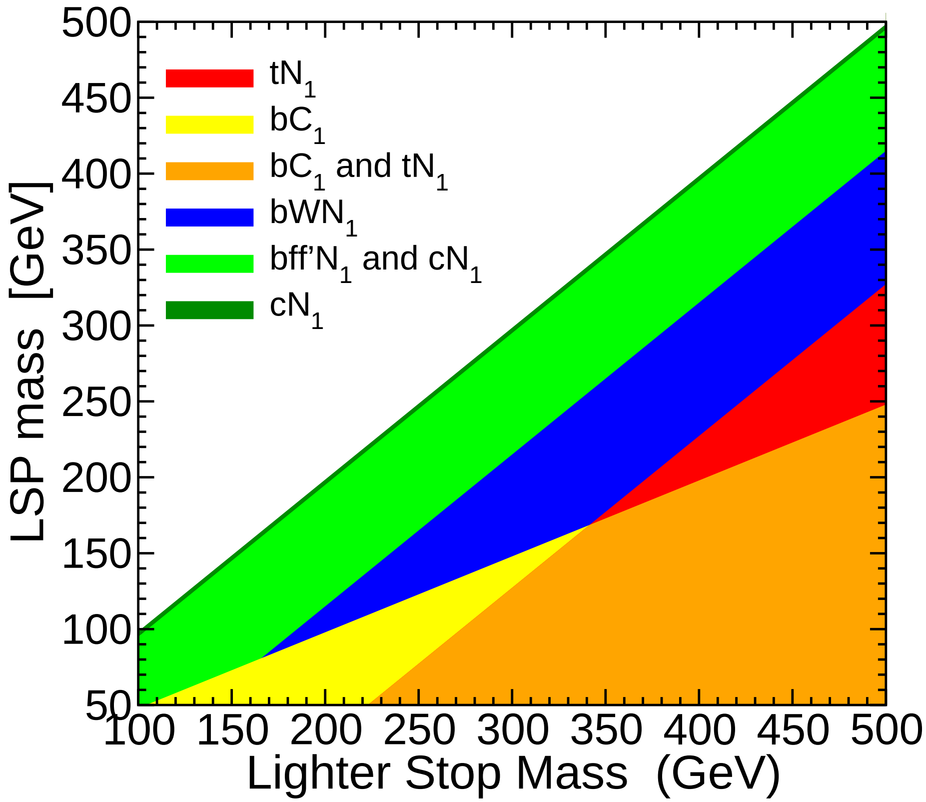
- NMSSM (extra tree-level coupling)
- Vector-like quarks with large Yukawa coupling to Higgs boson (non-decoupling loop effect)

NLO direct stop pair production cross-section from Prospino:



- Two orders of magnitude smaller than $(\tilde{g}, \tilde{u}, \tilde{d})$ of same mass
- 50% larger with $\sqrt{s} = 8$ TeV than at 7 TeV
- When decay products are soft, rely on extra radiated jets; only perhaps 10% of the rate contributes

Kinematically allowed decays, for unified gaugino masses (including mSUGRA) $M_1 = 0.5 M_2$ at the TeV scale:



Red, yellow, orange = 2-body

Blue = 3-body

Green = competition between 2-body flavor violating, 4-body decays

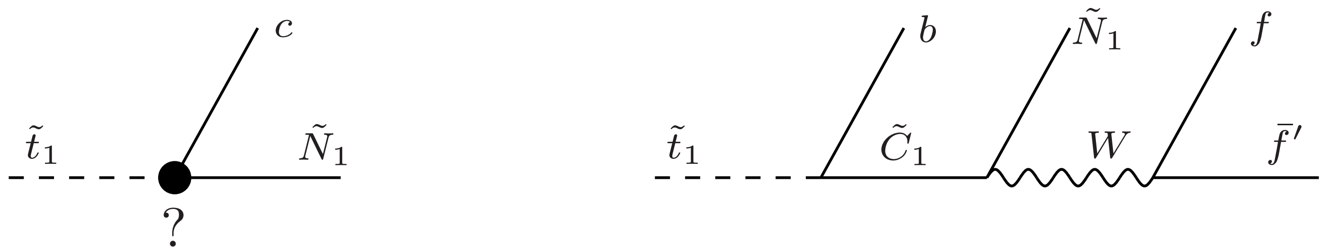
In green and blue regions, the top squark hadronizes before it decays.

Which decay wins in the light green region, $\Delta M = M_{\tilde{t}_1} - M_{\tilde{N}_1} < 85$ GeV?

$\tilde{t}_1 \to c\tilde{N}_1$ 2-body, flavor violating (wins for ΔM small)

$\tilde{t}_1 \to bf\bar{f}'\tilde{N}_1$ 4-body suppressed (wins for $\Delta M \sim 85$ GeV)

But, 2-body decay depends on unknown coupling:



Important: your favorite theorists, and their model and event simulation programs, don't know which one wins in general. Don't trust what those programs tell you! Both decays must be searched for when both are kinematically allowed.

Predictions rely on **assumptions**, like "Minimal Flavor Violation".

For stops produced in gluino/squark decays, the signal is easy and fun, even if the stops decay softly: same sign tops.

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

(Kraml and Raklev hep-ph/0512284, SPM 0807.2820, many others)

For example, same sign leptons:

$$pp \to \ell^{\pm}\ell'^{\pm}bbjj + X + E_T^{\rm miss}.$$

Can also replace the charm quarks with $bf\bar{f}'$, if that decay wins.

In the opposite extreme of a large mass difference,
$M_{\tilde{t}_1} - M_{\text{LSP}} > M_t$,

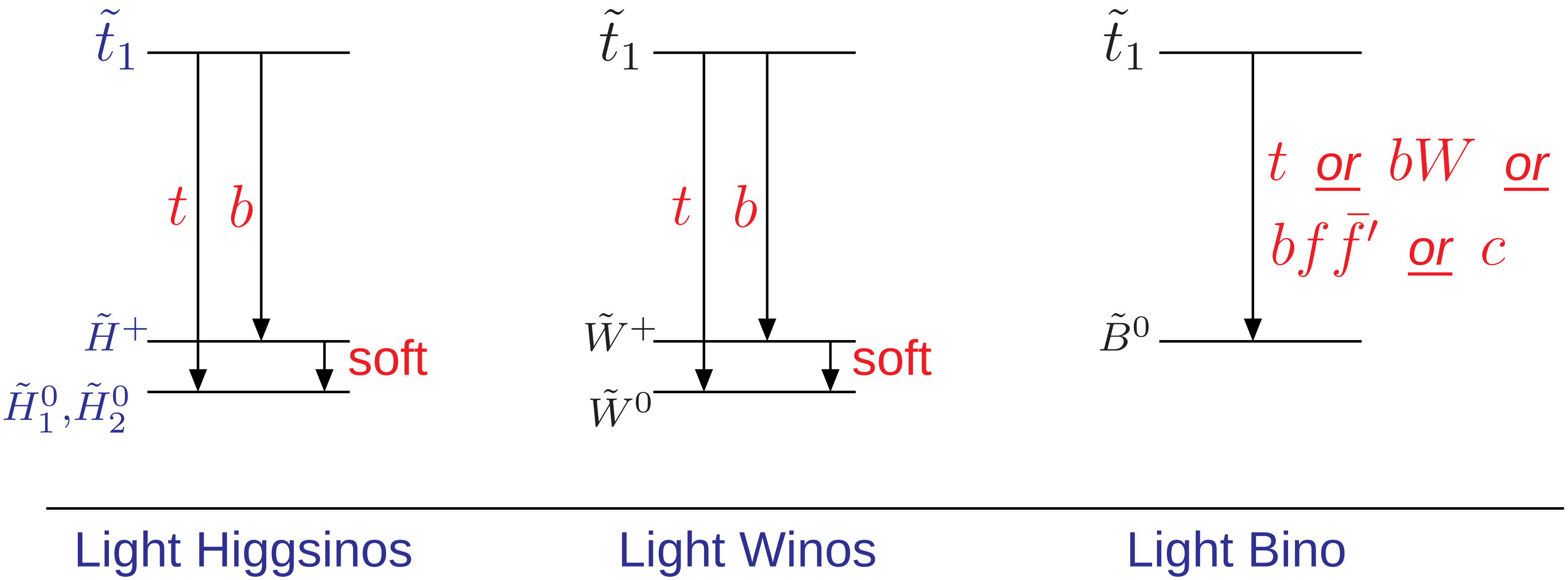
$$pp \to \tilde{t}_1 \tilde{t}_1^* \to t\bar{t} + E_T^{\text{miss}}$$

This direct production signal is also difficult by traditional methods, because of large $t\bar{t}$ background.

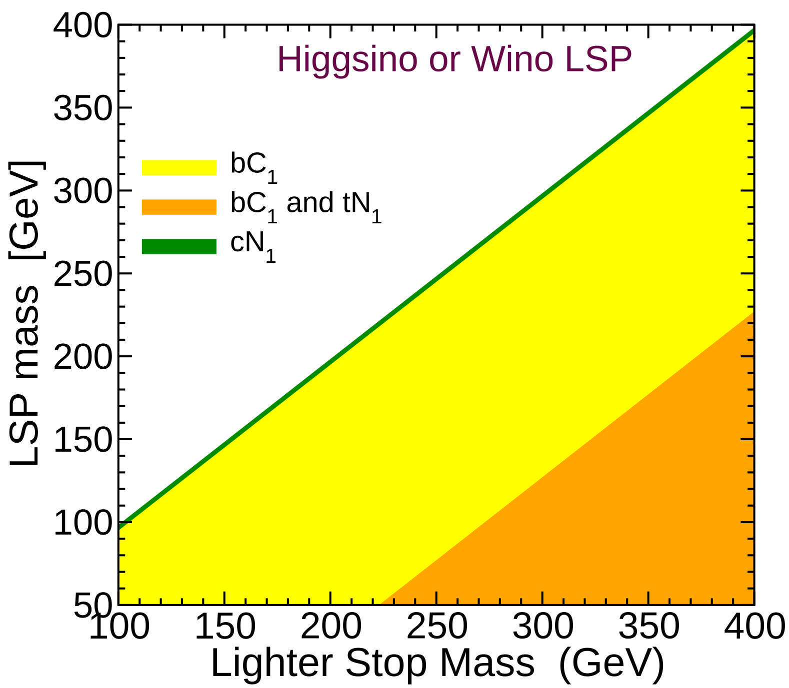
The tops can be tagged using fat jet analyses (both semi-leptonic and hadronic), and stops reconstructed.

Plehn, Spannowsky, Takeuchi, Zerwas, 1006.2833, 1102.0557, . . .

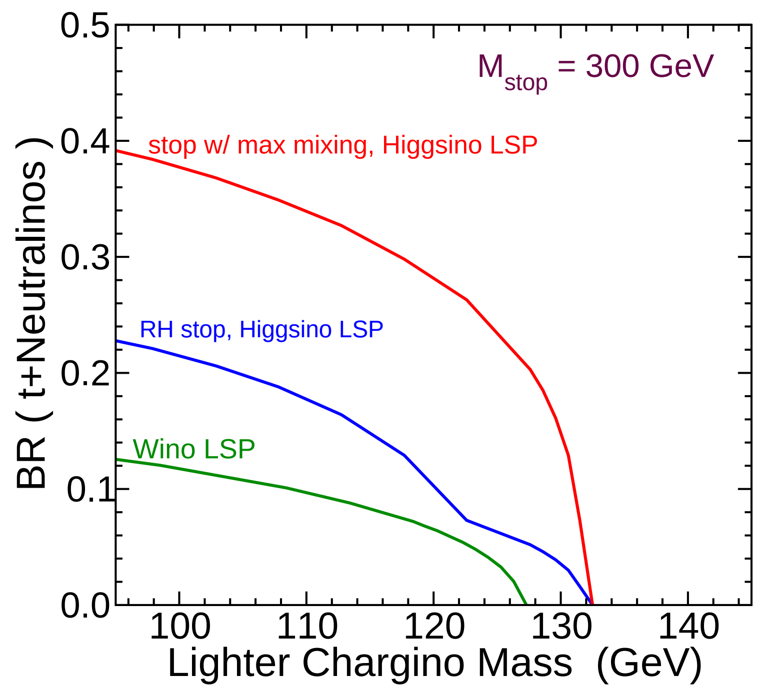
Other varieties of stop decays, non-mSUGRA and simplified models:



Map of kinematically allowed decays:



BR$(t\tilde{N}_i)$ depends on LSP, stop mixing:



Difficult if stops are produced only directly:

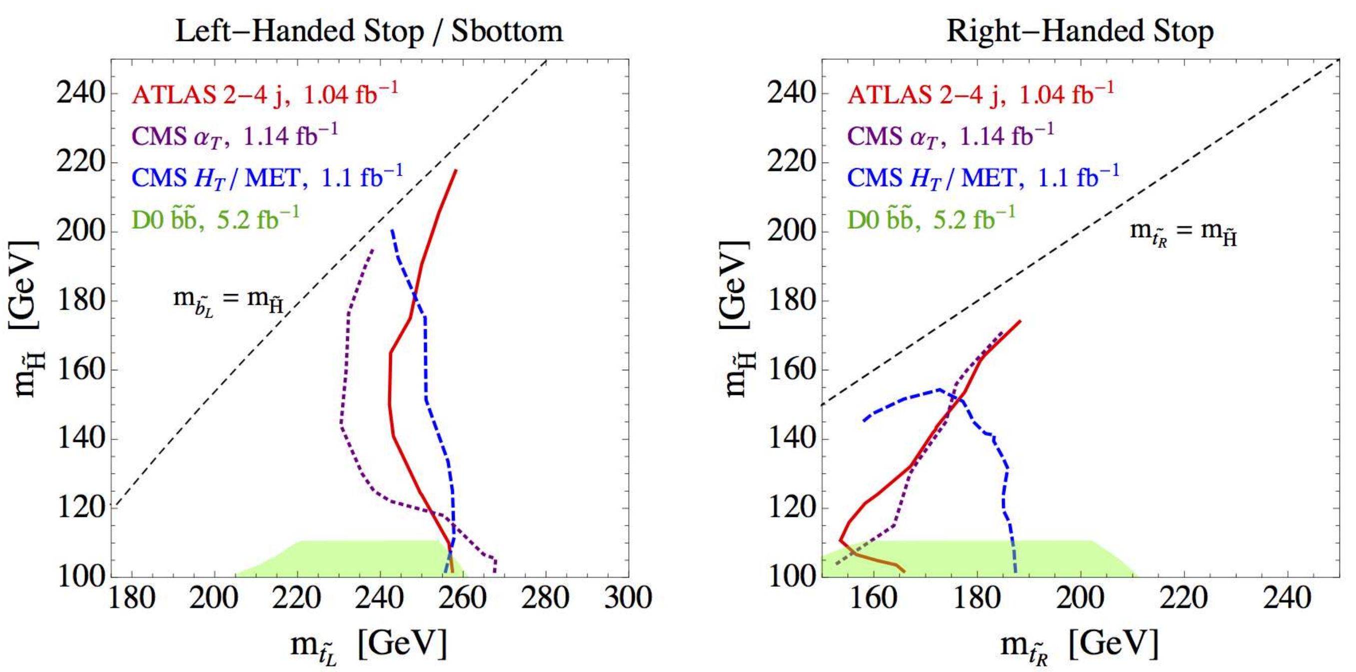
- If $M_{\tilde{t}_1} - M_{\tilde{N}_1}$ is large: small rate.
- If $M_{\tilde{t}_1} - M_{\tilde{N}_1}$ is small: soft decay products.

There is definitely room for ATLAS and CMS to exploit the stop-higgsino LSP and stop-wino LSP scenarios.

Papucci, Ruderman, Weiler `1110.6926` repurpose existing searches with 1 fb^{-1}:

$\tilde{t}_L \to b\tilde{H}^+ \to b\tilde{H}^0$ + soft, and $\tilde{b}_L \to b\tilde{H}^0$

$\tilde{t}_R \to b\tilde{H}^+ \to b\tilde{H}^0$



Other approaches to soft stops

Look for monojets or monophotons:

$$
\begin{aligned}
pp &\rightarrow \tilde{t}_1 \tilde{t}_1^* j \rightarrow j + \text{soft} + E_T^{\text{miss}} \\
pp &\rightarrow \tilde{t}_1 \tilde{t}_1^* \gamma \rightarrow \gamma + \text{soft} + E_T^{\text{miss}}
\end{aligned}
$$

Studies indicate that this is a difficult, long-term approach.

Carena, Freitas, Wagner 0808.2298, Drees, Hanussek, Kim 1201.5714

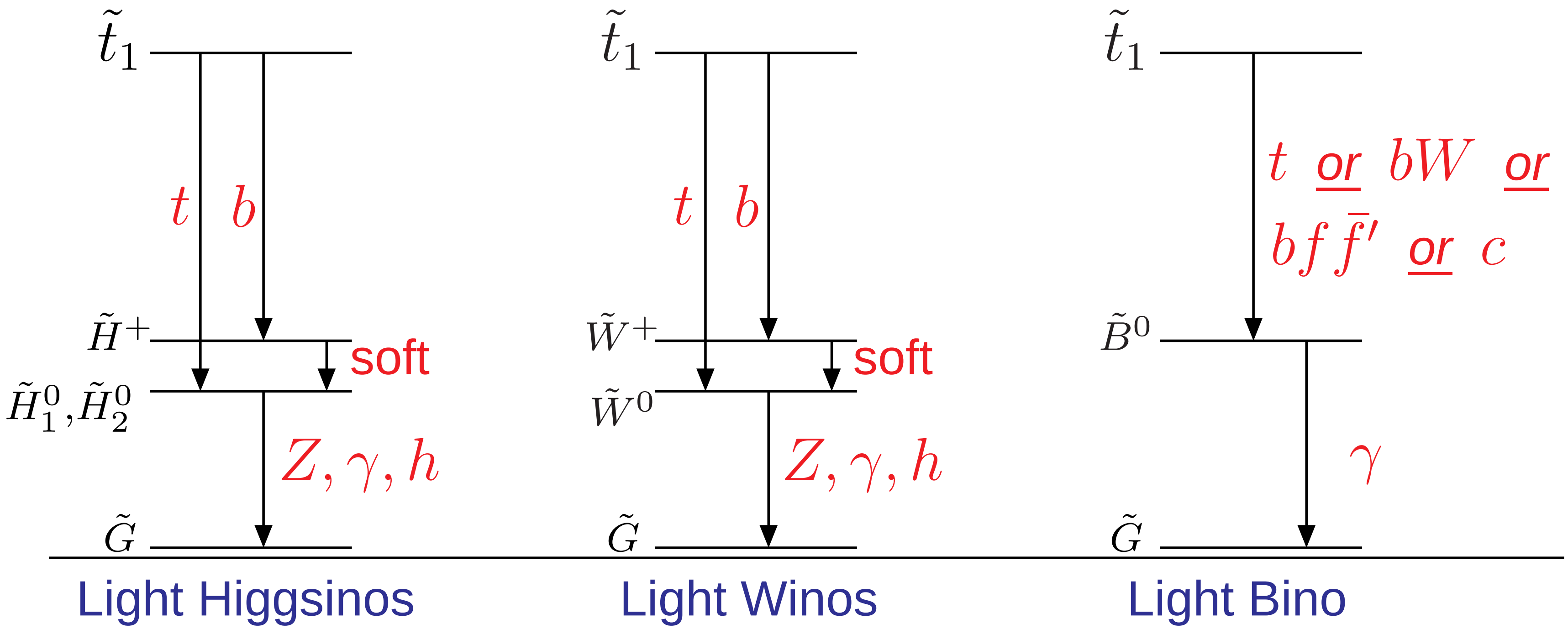
If $\tilde{t}_1$ has no allowed 2-body decays that conserve flavor ($M_{\tilde{t}_1} - M_{\text{LSP}} \lesssim 85$ GeV and $M_{\tilde{t}_1} \lesssim M_{\tilde{C}_1} + 5$ GeV), then it hadronizes before decaying.

Stoponium has a BR$(\gamma\gamma)$ = 0.5%. The rate is low, but it would be a unique opportunity: a clean mass peak in SUSY!

Drees and Nojiri hep-ph/9312213, SPM 0801.0237

We should be looking for monojets, monophotons and diphoton peaks anyway!

In GMSB models, add extra γ, Z, or h to each decay:



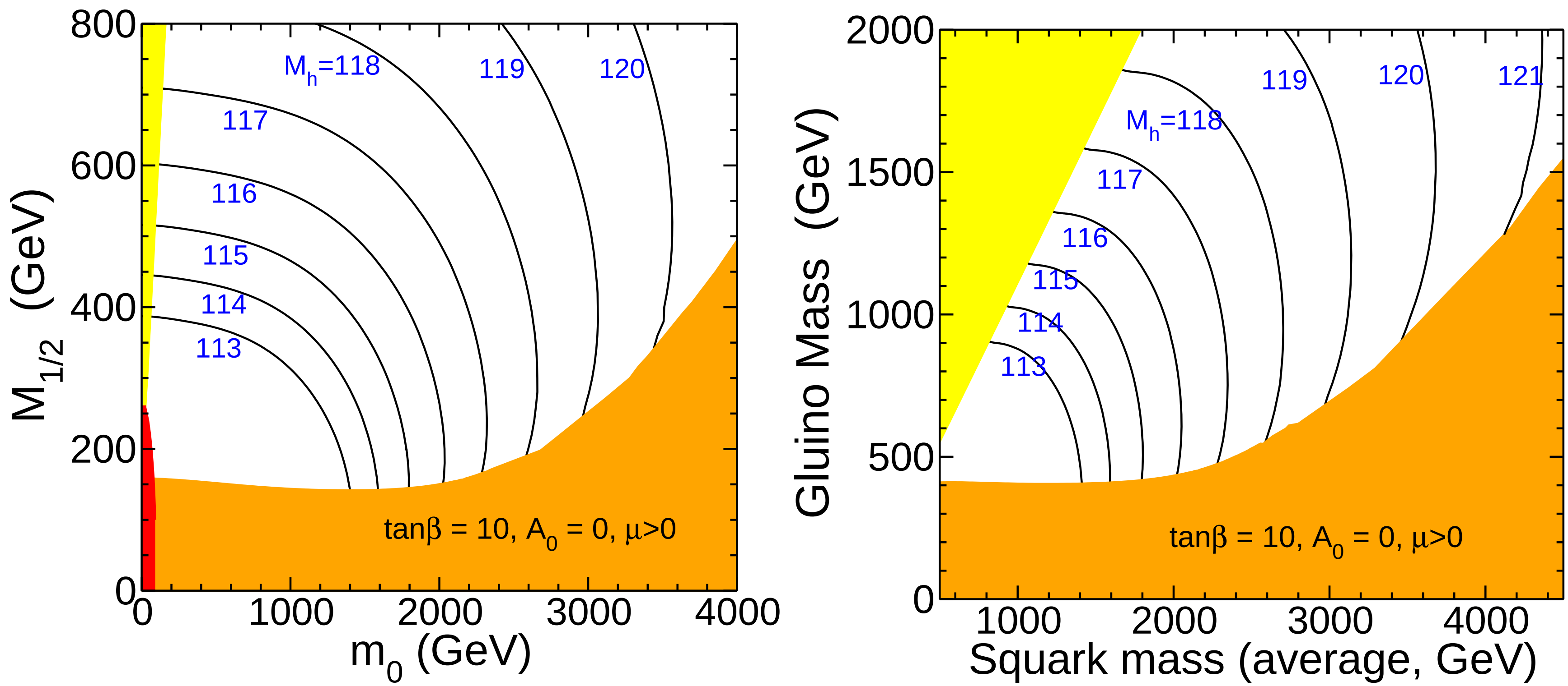
What should be done with mSUGRA = CMSSM searches now, especially if $M_h = 125$ GeV?

ATLAS, CMS searches in past:

- $A_0 = 0$, ensures small stop mixing angle $\theta_{\tilde{t}}$
- $\tan\beta = 10$, not optimal for $M_h = 125$ GeV.
- $\mu > 0$

Most of the models excluded by ATLAS and CMS with these choices cannot accomodate LEP2 limit on M_h, let alone $M_h = 125$ GeV.

M_h in present LHC search planes for mSUGRA, with $\tan\beta = 10$ and $A_0 = 0$:



Does not get anywhere close to $M_h = 125$ GeV.

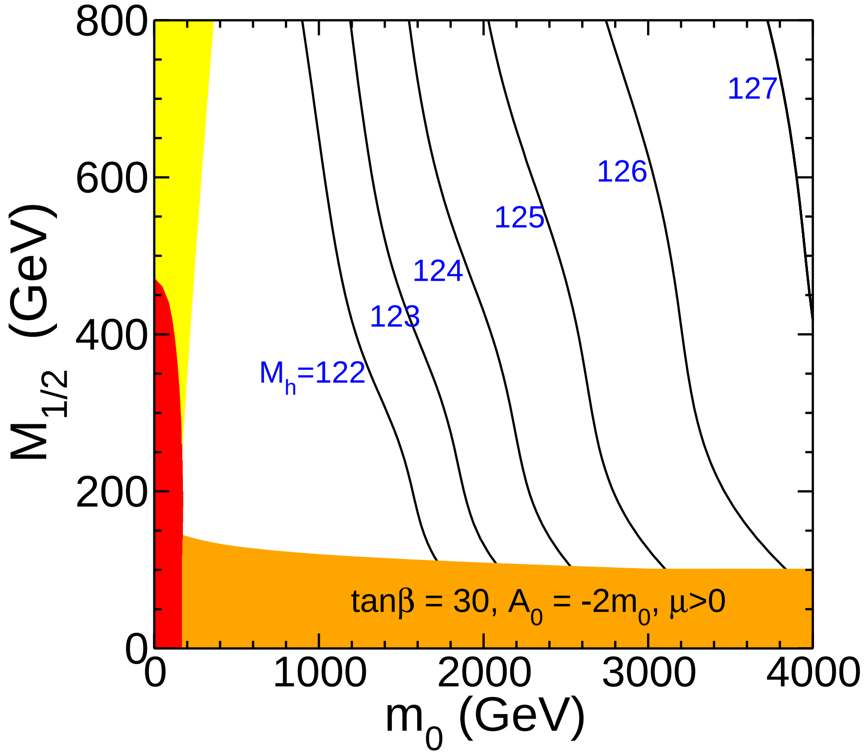
Incidental suggestion: even for mSUGRA, exclusion contours should be presented in squark-gluino mass plane, not (just) $m_0, M_{1/2}$ plane. Physical masses are more useful and robust than input parameters!

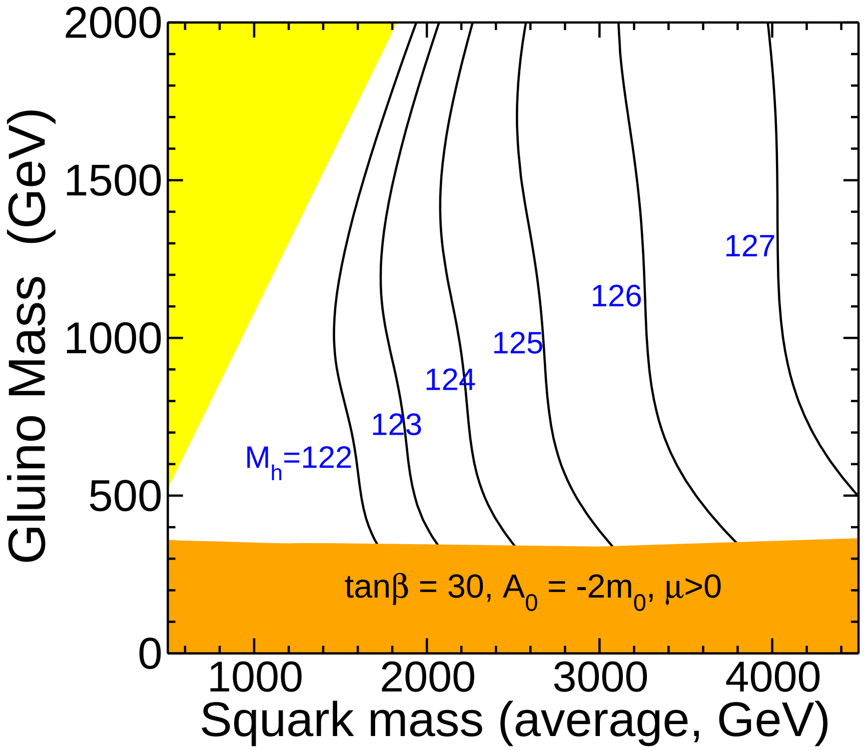
Suggestion: add/change default mSUGRA searches to

$$\tan\beta = 30, \quad A_0 = -2m_0, \quad \mu > 0.$$

This is much closer to the optimal “M_h-max” scenario for $\theta_{\tilde{t}}$, so that a prediction $122 < M_h < 128$ can be achieved for much lower squark masses.

M_h in mSUGRA with $\tan\beta = 30$ and $A_0 = -2m_0$:

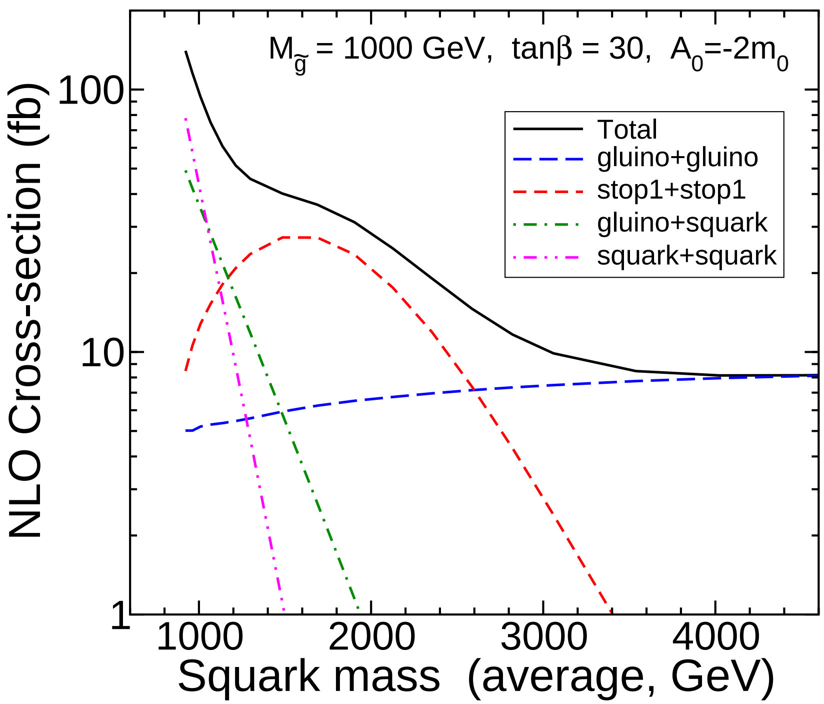




Features:

- $122 < M_h < 128$ compatible with any gluino mass.
- Average squark mass as light as 1500 GeV; stops much lighter

What characterizes these models?



Varying m_0 probes the relative importance of u, d squarks (low m_0), top squarks (intermediate m_0), and gluinos (high m_0) to the signal.

Important processes for the $M_h = 125$ region of mSUGRA:

$$pp \to \tilde{q}\tilde{q} \to \text{jets} + E_T^{\text{miss}},$$

$$pp \to \tilde{g}\tilde{q} \to t\bar{t} + \text{jets} + E_T^{\text{miss}},$$

$$pp \to \tilde{t}_1\tilde{t}_1^* \to t\bar{t} + E_T^{\text{miss}},$$

$$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t} + E_T^{\text{miss}}.$$

“Stupidity is coming to a conclusion.”

–Anonymous (?)