Natural SUSY's Last Hiding Places

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at the Fermilab LPC, July 22, 2014

The Big Question

We want the LHC to tell us: **is electroweak symmetry breaking *natural*?**

Early indications point to “no.” But there’s still some room for (more or less) natural new physics that has *hidden* so far.

How can naturalness hide, and how do we coax it out if it is hiding?

EWSB in SUSY

Minimize potential with respect to Higgs VEVs v_u and v_d to get two equations (e.g. Martin SUSY Primer hep-ph/9709356):

$$m_{H_u}^2 + |\mu|^2 - b\cot\beta - (m_Z^2/2)\cos(2\beta) \;=\; 0,$$
$$m_{H_d}^2 + |\mu|^2 - b\tan\beta + (m_Z^2/2)\cos(2\beta) \;=\; 0.$$

These are **tree-level** results in the **MSSM**. A 125 GeV Higgs means **either: large loops or beyond MSSM**. But the main effect is to replace m_Z in these formulas with a corrected number of the same order of magnitude.

EWSB in SUSY

Rearranging a bit: M_U^2, M_D^2 the masses of the up-type and down-type Higgs in the Lagrangian, *b* the mass mixing:

$$M_U^2 + M_D^2 = \frac{2b}{\sin(2\beta)} = m_A^2, \quad \frac{1}{2} m_Z^2 = \frac{M_D^2 - M_U^2 \tan^2\beta}{\tan^2\beta - 1}.$$

A **natural** theory of EWSB is one where there are **no large cancellations** either **among** terms in these equations or **within** a single term.

Constrains:

$$|\mu|^2 \lesssim m_Z^2 \text{ (higgsinos)}$$

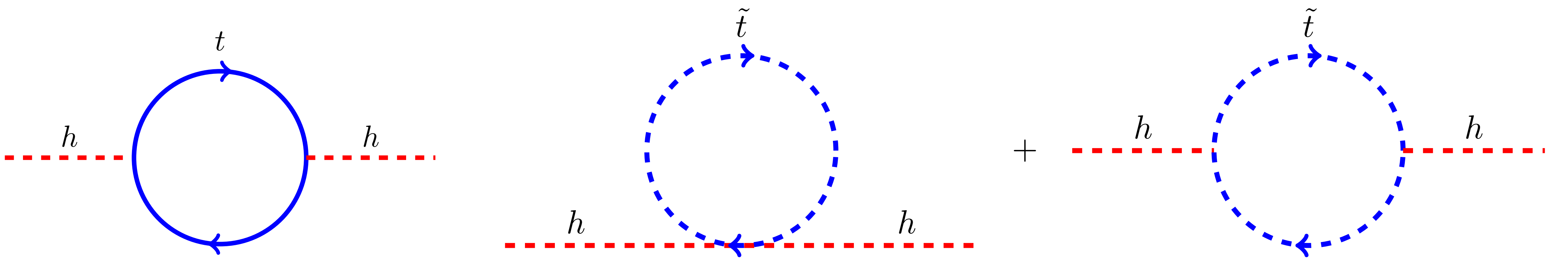
$$\left|m_{H_u}^2\right| \lesssim m_Z^2 \text{ (higgs)}$$

$$m_{H_d}^2 \lesssim m_Z^2 \tan^2\beta. \text{(heavy Higgses } H^{0,+/-}, A^0\text{)}$$

$$M_U^2 = \left(m_{H_u}^2\right)_{\text{tree}} + \left(m_{H_u}^2\right)_{\text{loop}} + |\mu|^2$$

(stops, gluinos via the loop term)

Stops & Naturalness

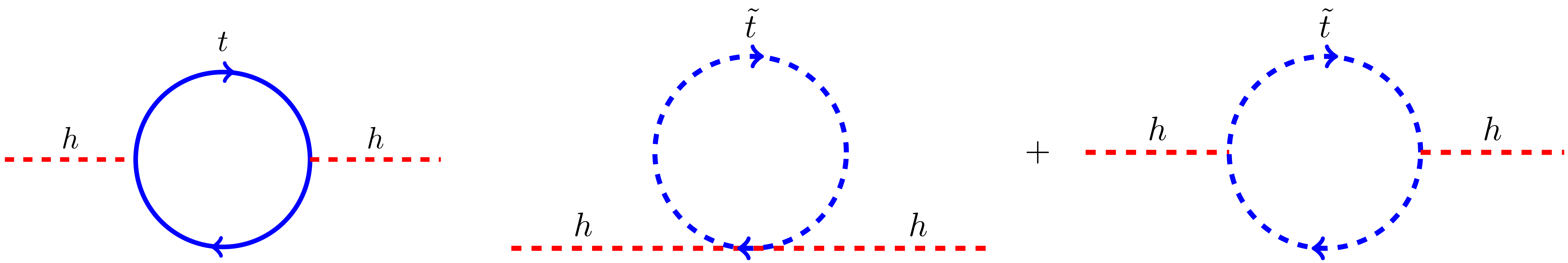


Large quantum corrections to the Higgs mass[2] term, if the stops are heavy or highly mixed:

$$\delta m_{H_u}^2 = -\frac{3}{8\pi^2} y_t^2 \left(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2 \right) \log \frac{\Lambda}{\mathrm{TeV}}.$$

We expect stops to be below about 500 to 700 GeV, if we want to avoid more than a factor of 10 tuning (already not really natural!) (e.g. 1110.6926 Papucci et al.)

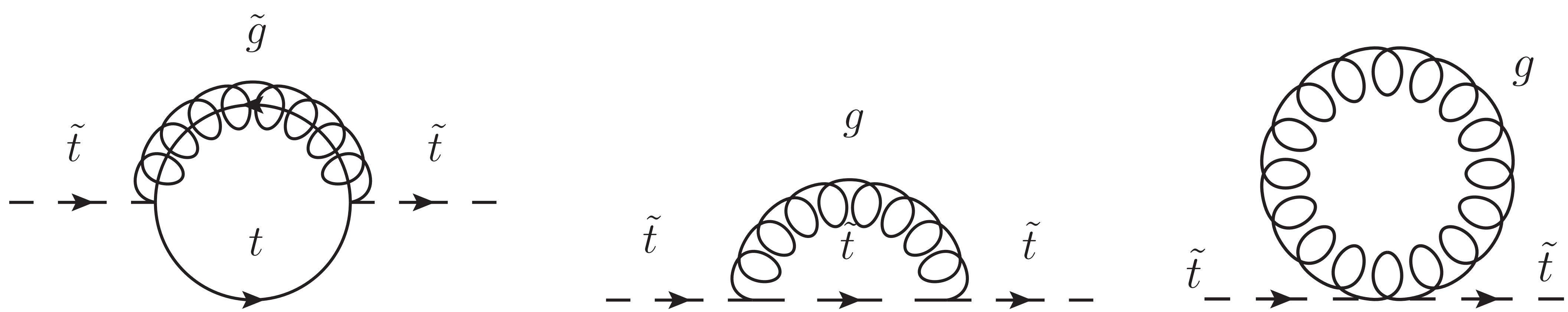
Stops & Naturalness



We're already seeing significant constraints on the natural stop parameter space. I will come back to this in much greater detail soon.

Naturalness and Gluinos

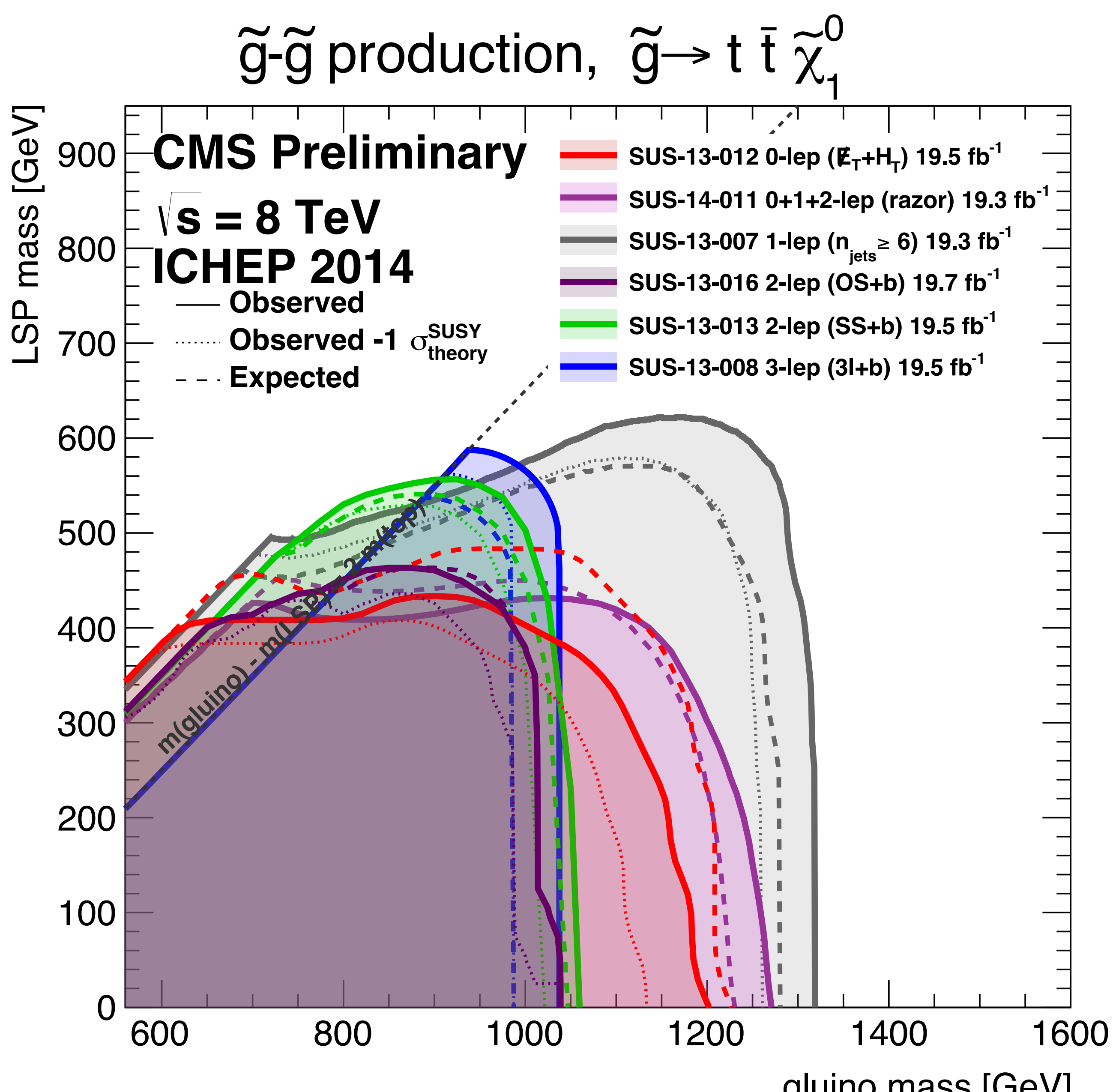
We need the stop to be relatively light for naturalness of a light Higgs. But the stop is itself a scalar field, and can get quadratic corrections!

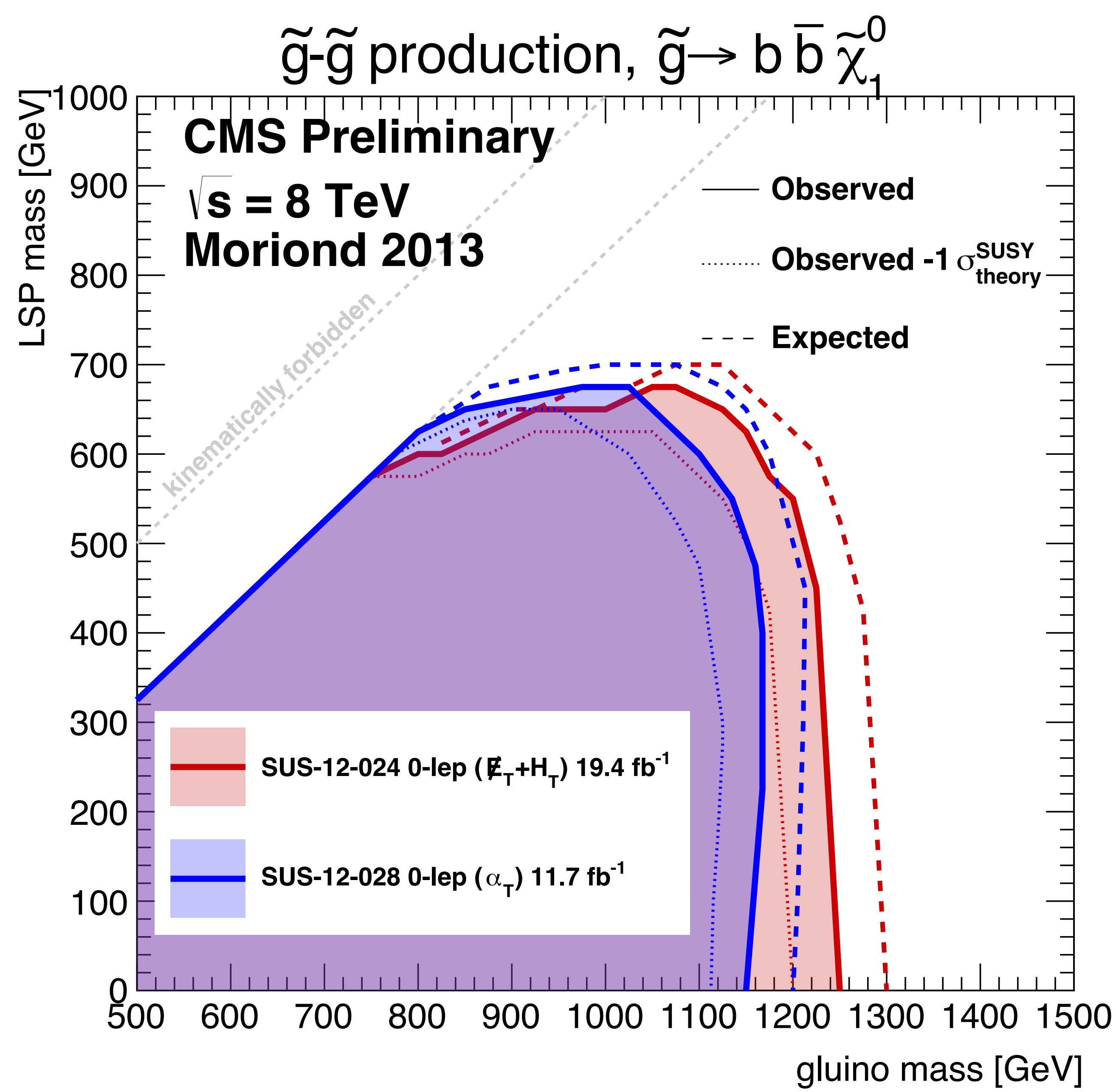


Large corrections come from the gluino, which hence should be light (below about 1.5 TeV). As a color octet, the gluino has a large production cross section at the LHC.

Gluinos

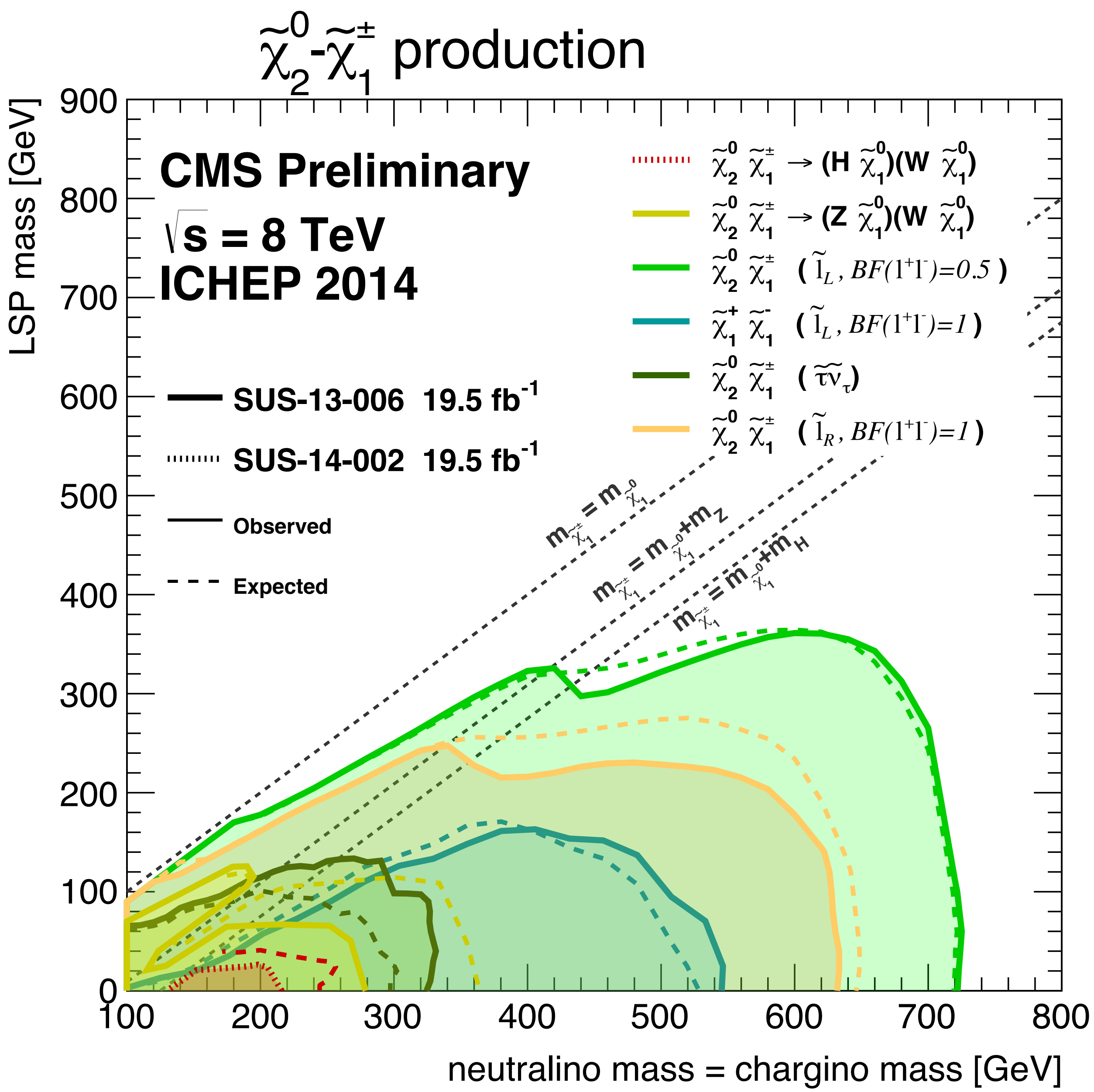
Gluino mass bounds are now above a TeV; e.g., 1.3 TeV if gluino decays through stops.





Electroweakinos?

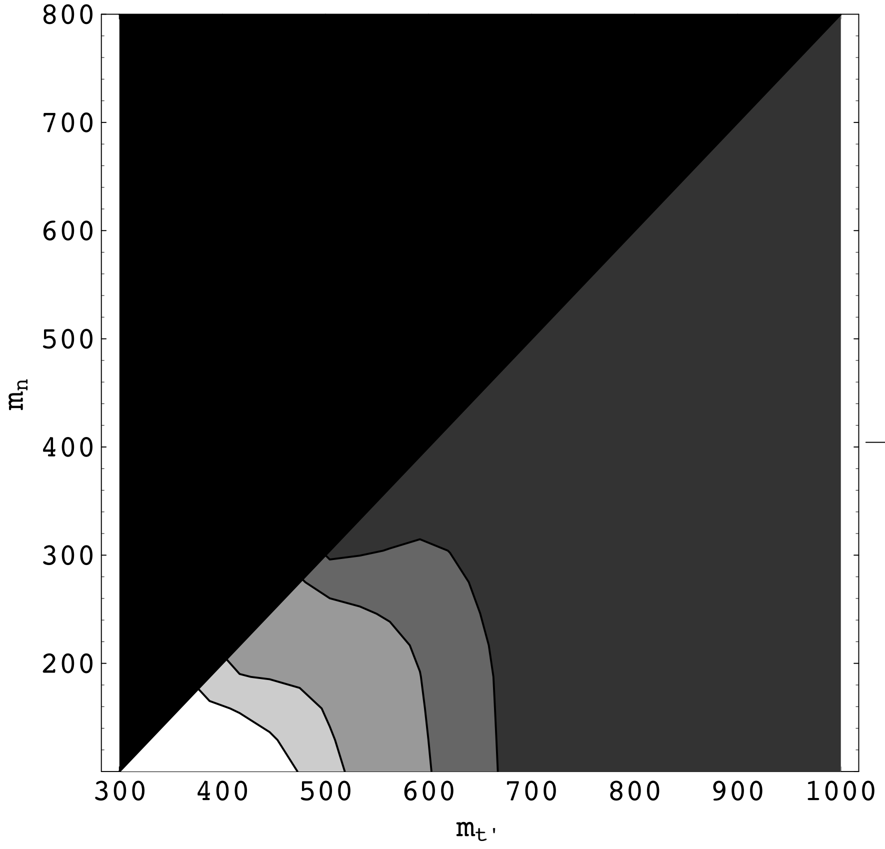
Superpartners of Higgs and electroweak gauge bosons are relatively unconstrained; limits mostly in scenarios that inflate the branching fraction to leptons:

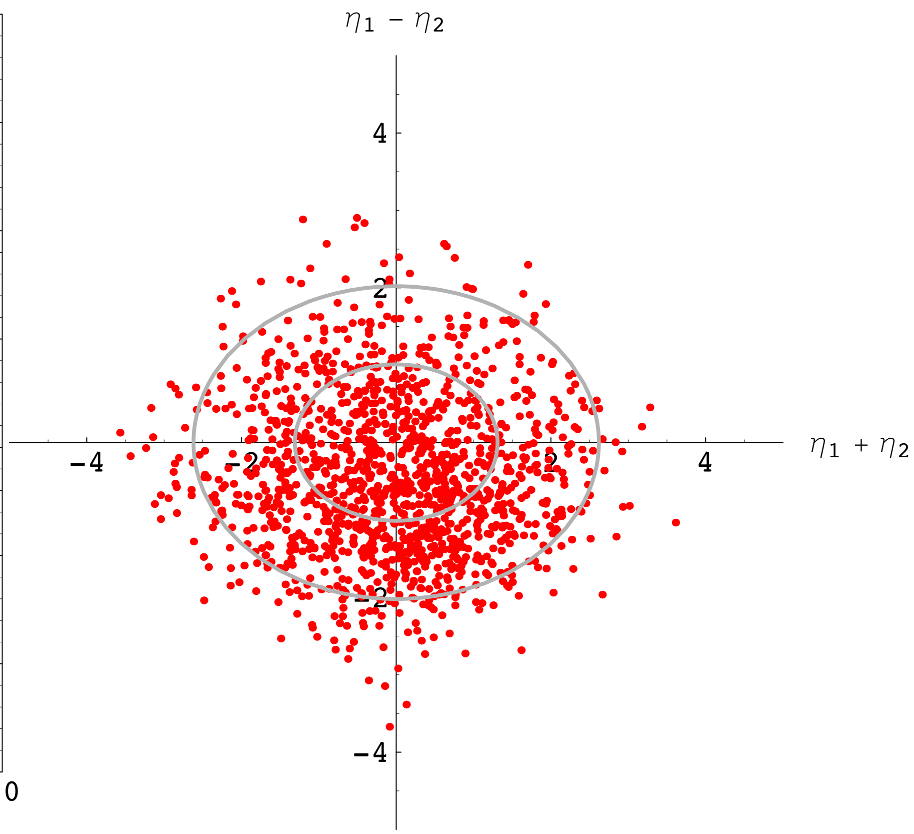


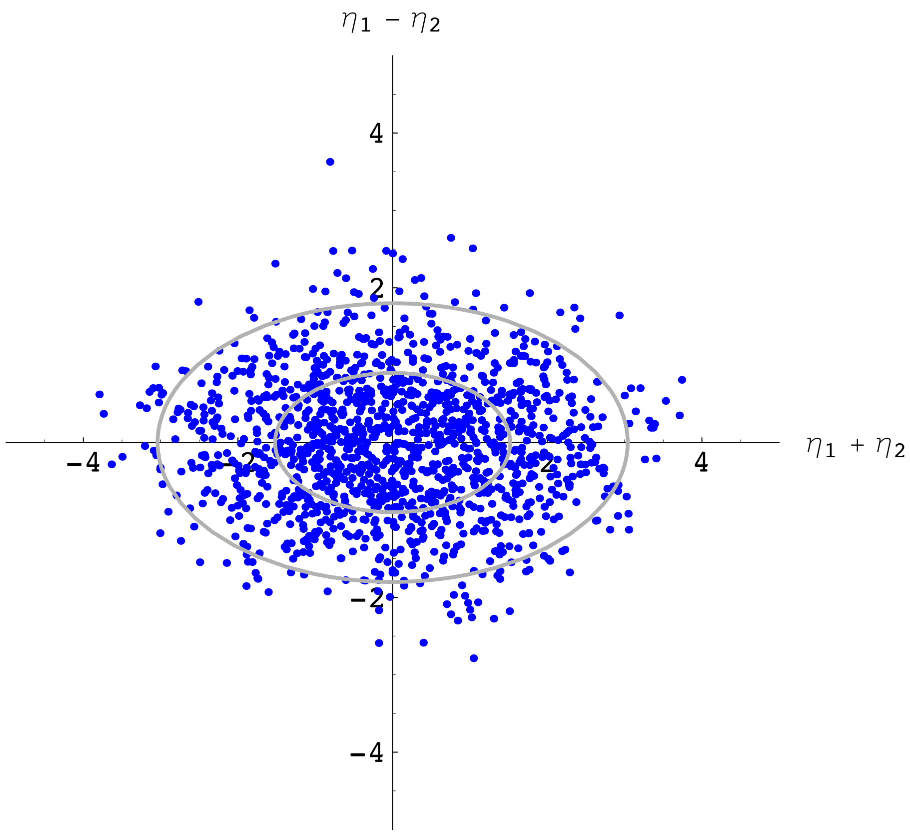
Naturalness predicts light Higgsinos, but direct production of Higgsinos at the bottom of the spectrum is hard to probe.

Stop Hunting

A long-term interest of mine, starting with hep-ph/0601124 with Patrick Meade on stop/neutralino simplified models:



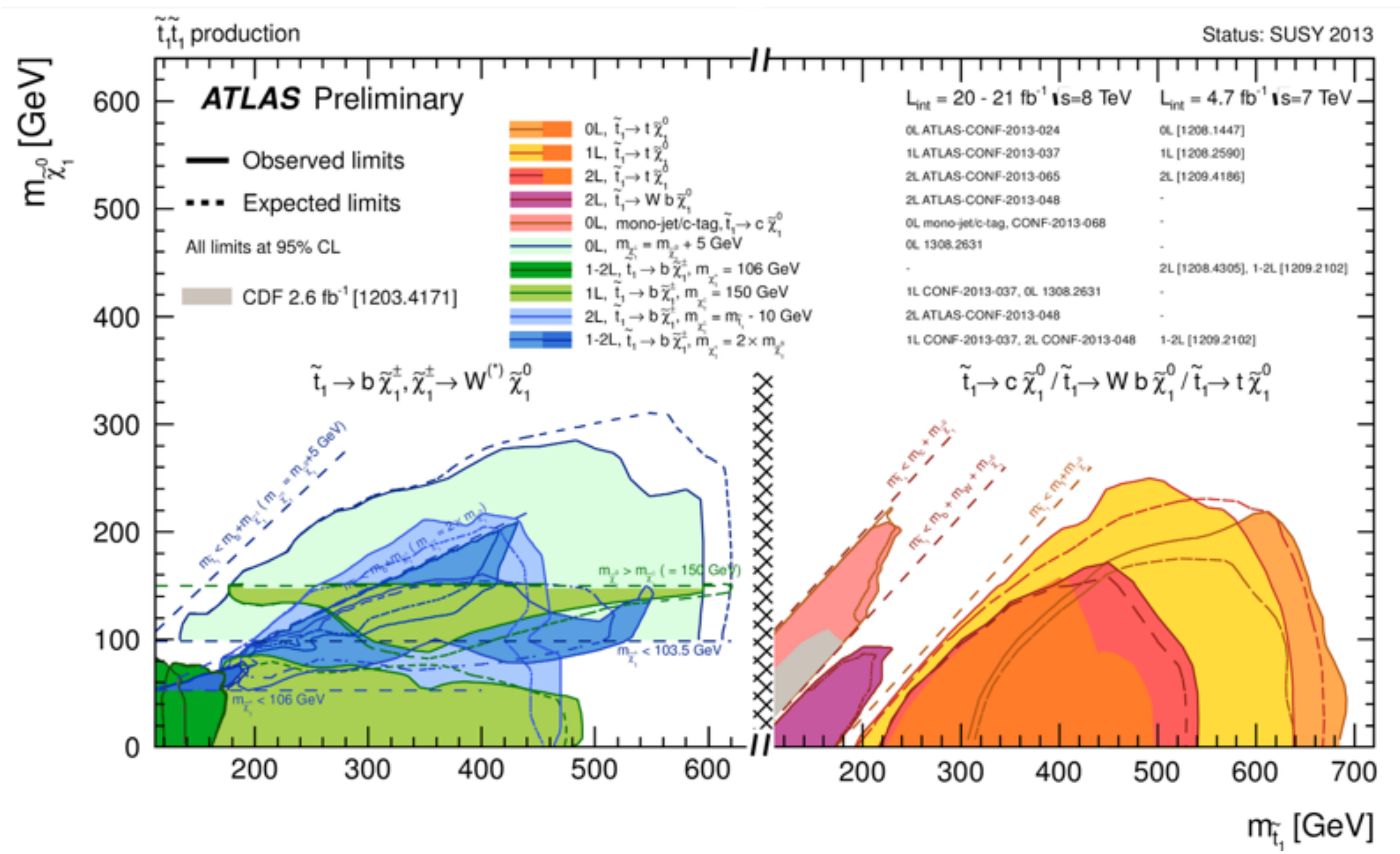




At the time, we were sure stops would be quickly discovered and the challenge would be using subtle angular differences like those at right to check their spin.

The Unnatural Truth?

Our advocacy of simplified models has been vindicated. Our confidence in naturalness, less so. **Where are the stops?**



The Higgs looks SM-like

A low-energy theorem tells us stops correct Higgs couplings to gluons or photons:

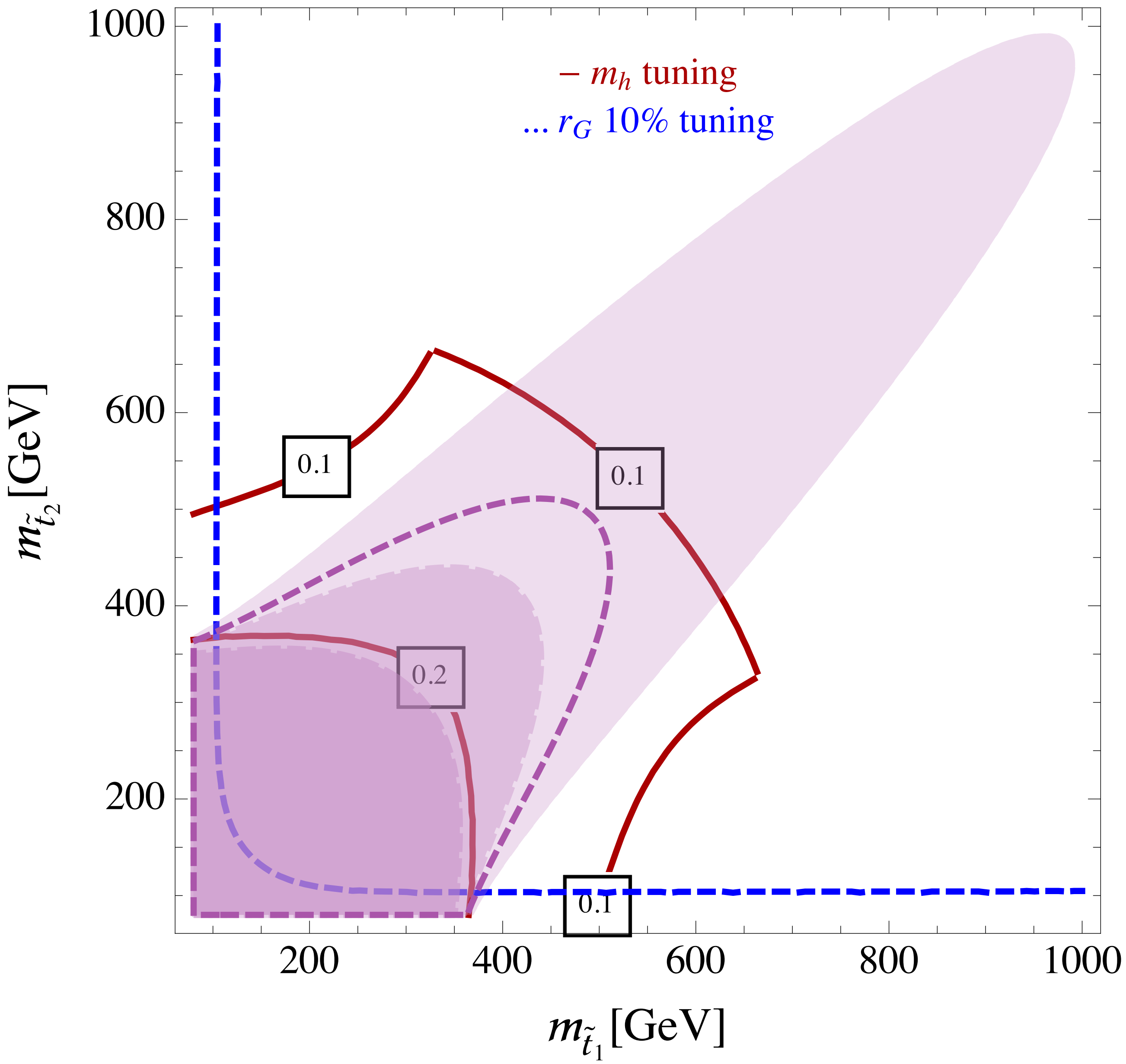
$$\mathcal{A}_{\tilde{t}-\mathrm{loop}}(gg \to h) \propto \frac{\partial \log \det M_{\tilde{t}}^2}{\partial v} \sim y_t m_t \frac{\tilde{m}_Q^2 + \tilde{m}_u^2 - X_t^2 \sin^2\beta}{\tilde{m}_Q^2 \tilde{m}_u^2 - X_t^2 m_t^2 \sin^2\beta}$$

For light enough stops, can only avoid a big correction via a sizable mixing term X_t. Implies tuning of the coupling.

For any pair of *physical* stop masses, there's a *maximum* X_t. (On the diagonal, $X_t = 0$: symmetric matrix with off-diagonal term will *always* have two unequal eigenvalues.)

So: robust bound on light stops.

Stop constraints



J. Fan and MR, 1401.7671

Result will be a little weaker after recent CMS Higgs to gamma gamma update!

Dead minimum factor of ~5 tuning, even without using direct stop searches, gluino searches, etc. “Stealth” can only help so much. Most models much worse.

Direct Searches

As we've already seen, direct searches probe stops up to ~700 GeV. But they *assume* particular decay modes.

Two main roles for theorists in ensuring broader coverage:

1. Fill gaps in existing searches through better observables.

2. Propose new search channels and simplified models that cover more of model space.

I'll give examples of both.

The Unnatural Truth?

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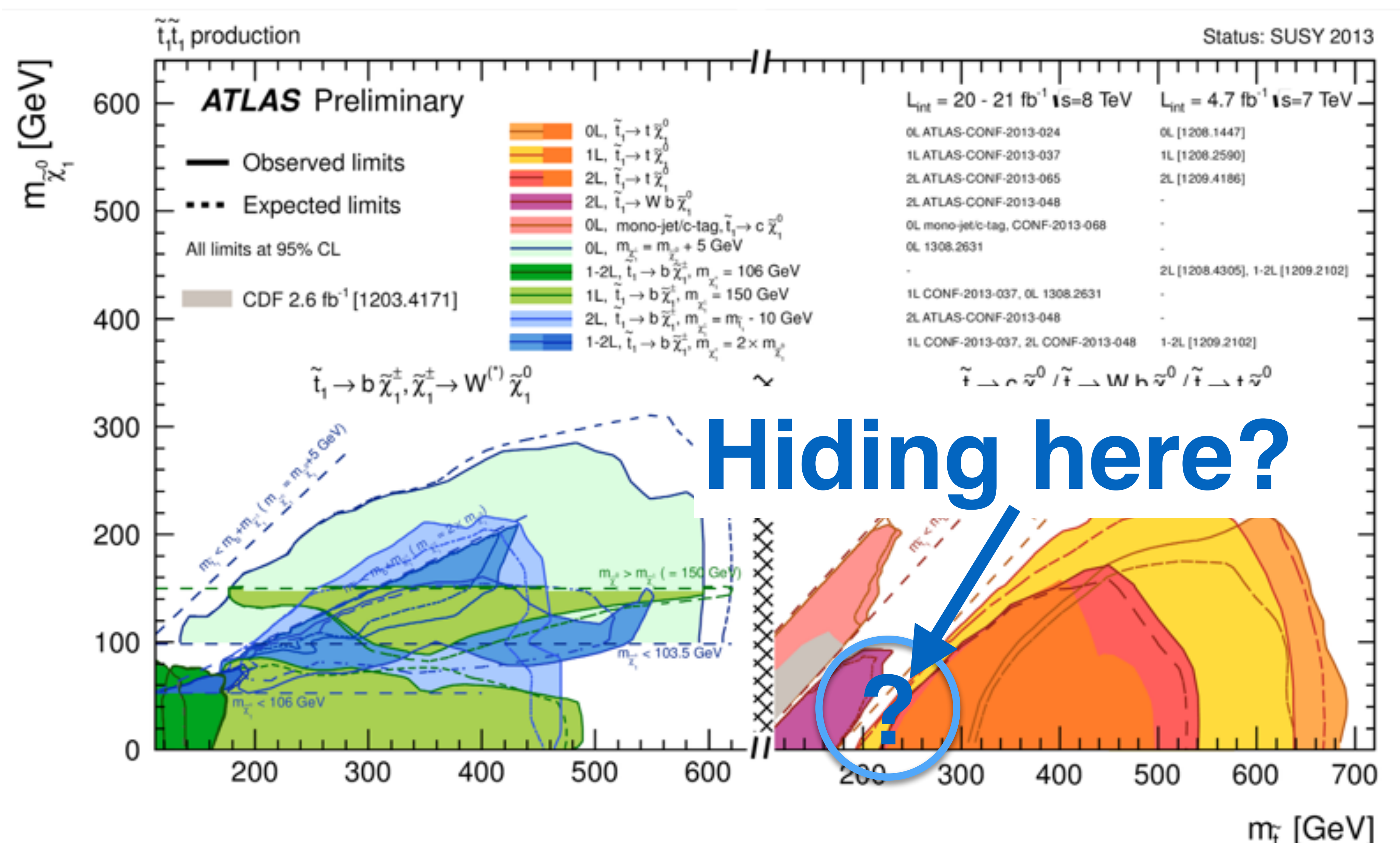
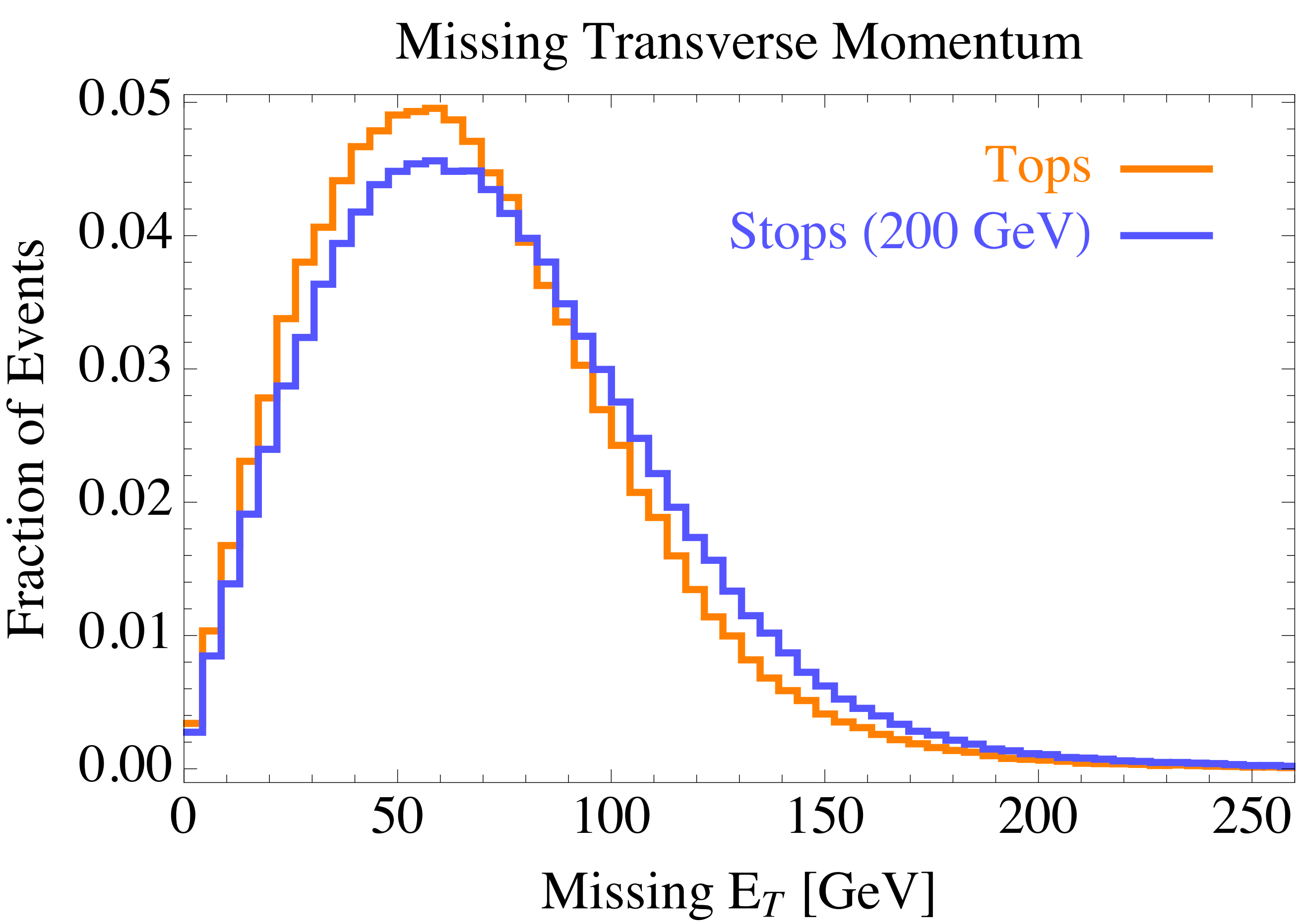
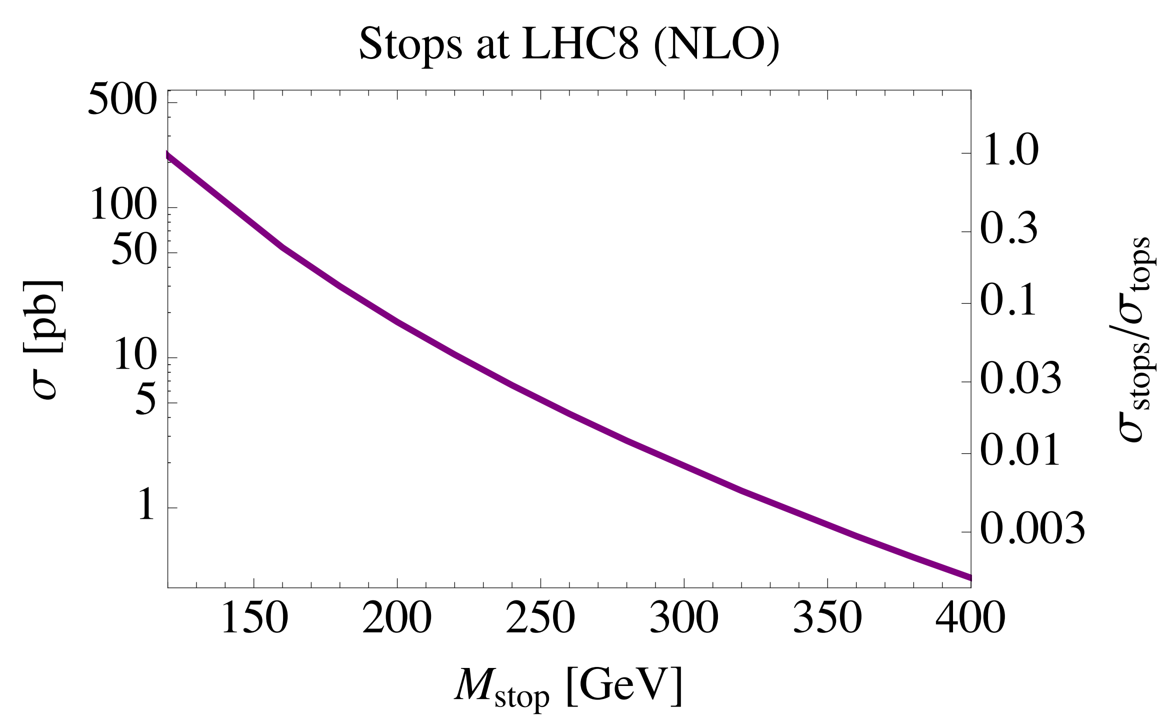


The Stealthy Stop

In the case $m_{\tilde{t}} \approx m_t \gg m_{\tilde{\chi}^0}$, the stop decays to a top and a very soft neutralino. This is kinematically nearly indistinguishable from direct $t\bar{t}$ production.



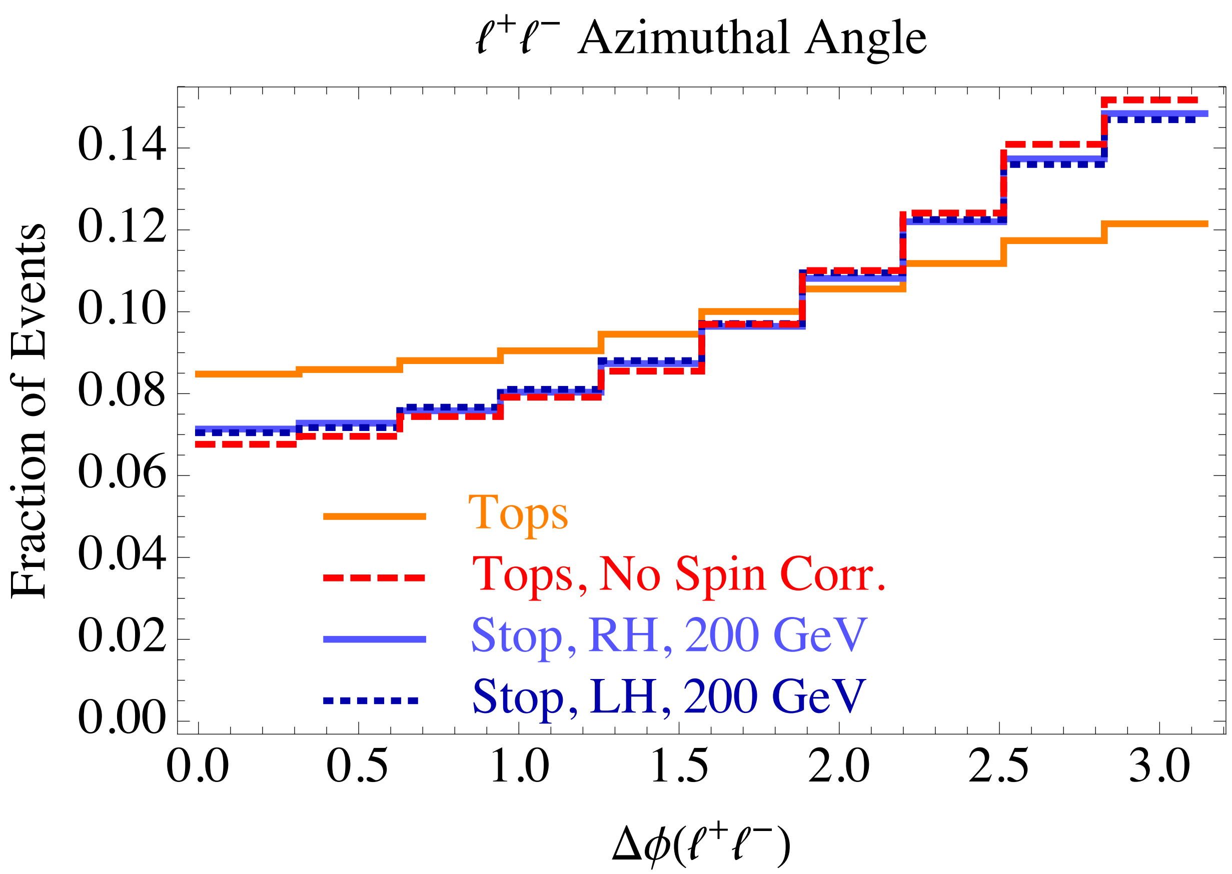
Z. Han, A. Katz, D. Krohn and MR, arXiv:1205.5808.



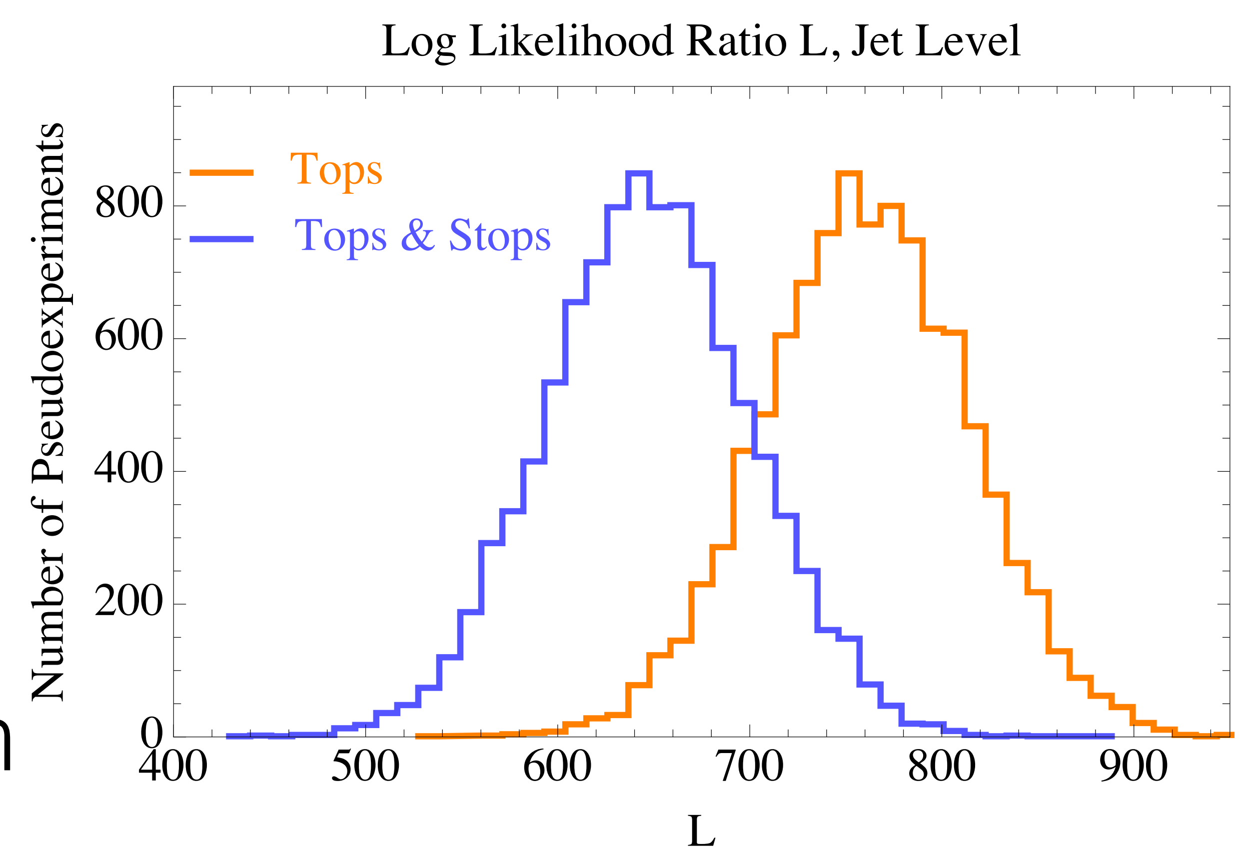
Small fraction of top cross section: hard to see!

Spin Correlations

This is one case where subtle angular deviations could be key to discovery:

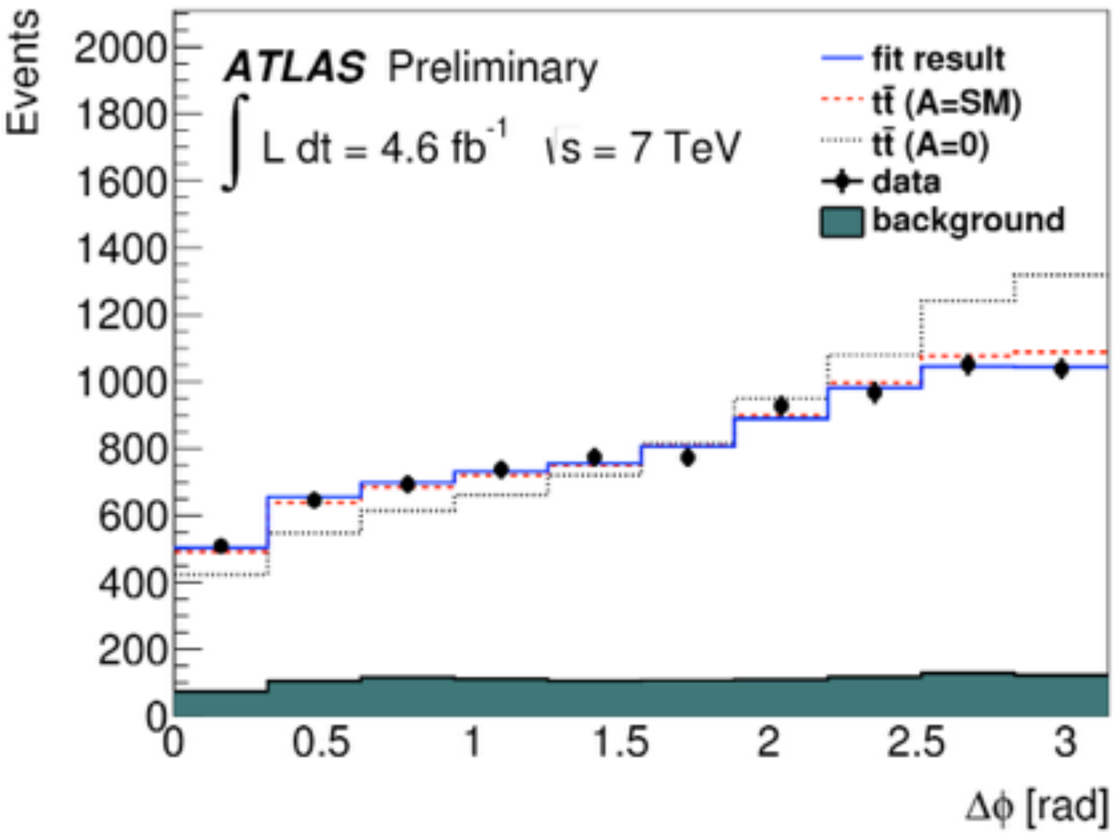


Stops, being scalars, look a lot like tops with no spin correlations.



Estimate of likelihoods for 200 GeV stops. (See also update from Z. Han, A. Katz, arXiv:1310.0356)

7 TeV Looks SM-Like.
8 or 13 TeV: Derive Bound?



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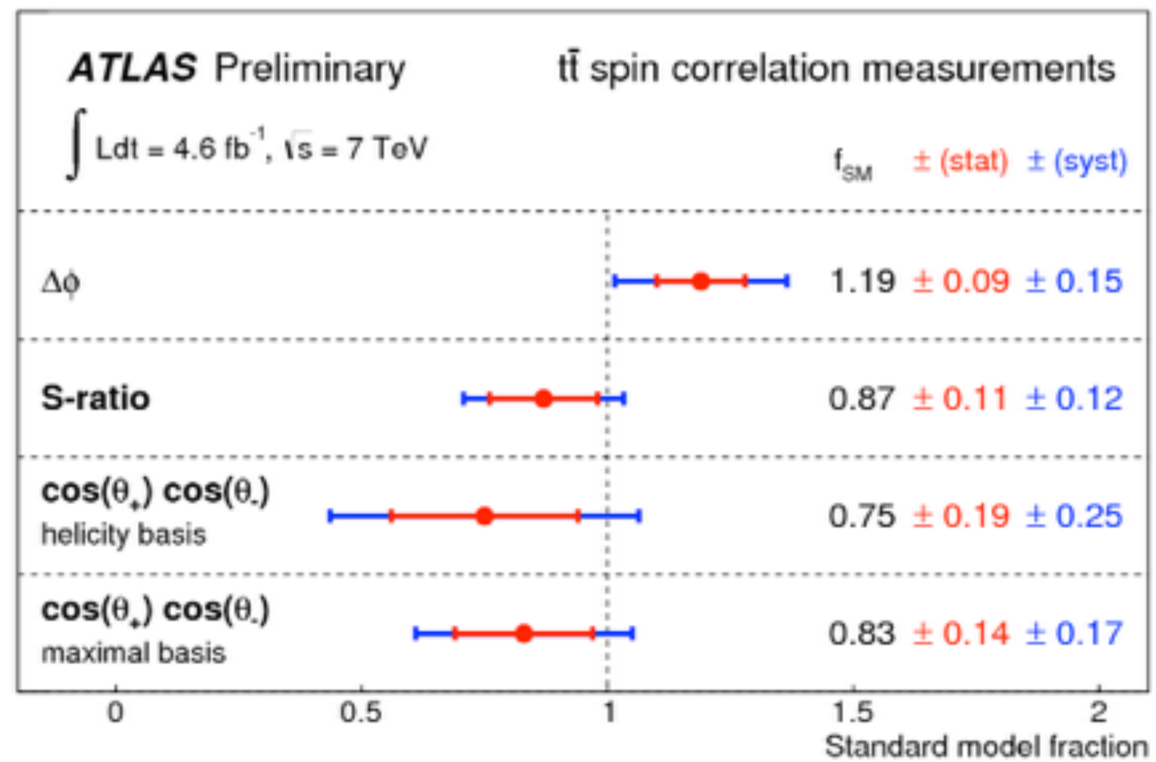
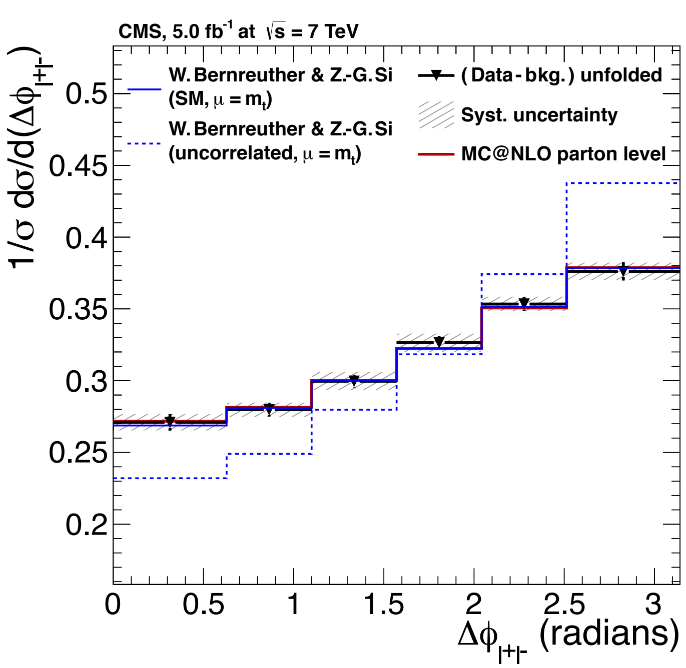
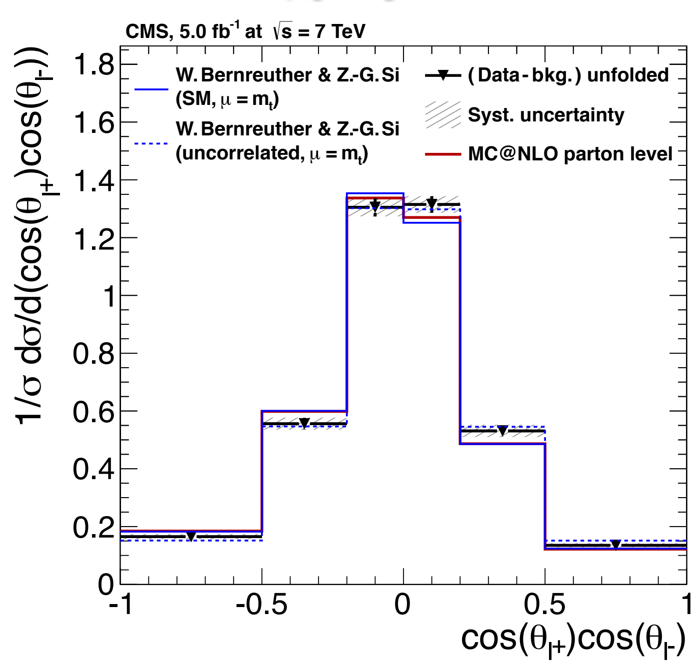
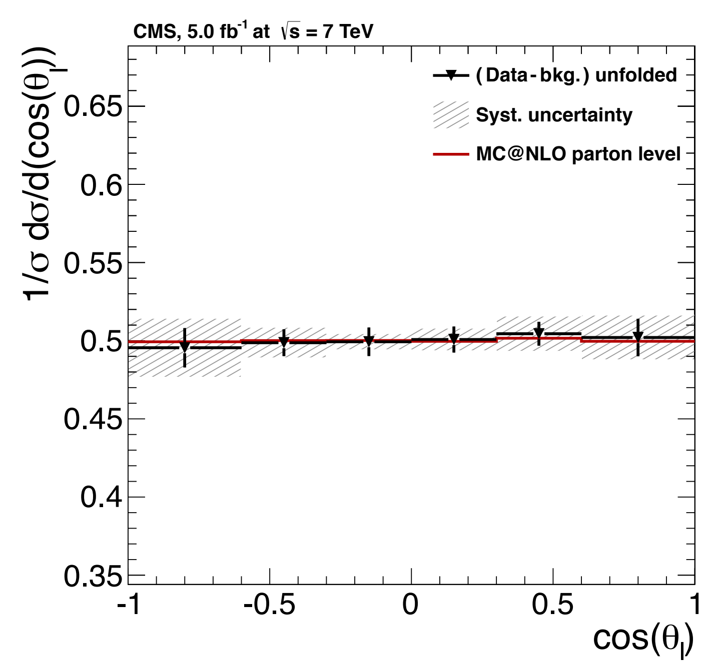




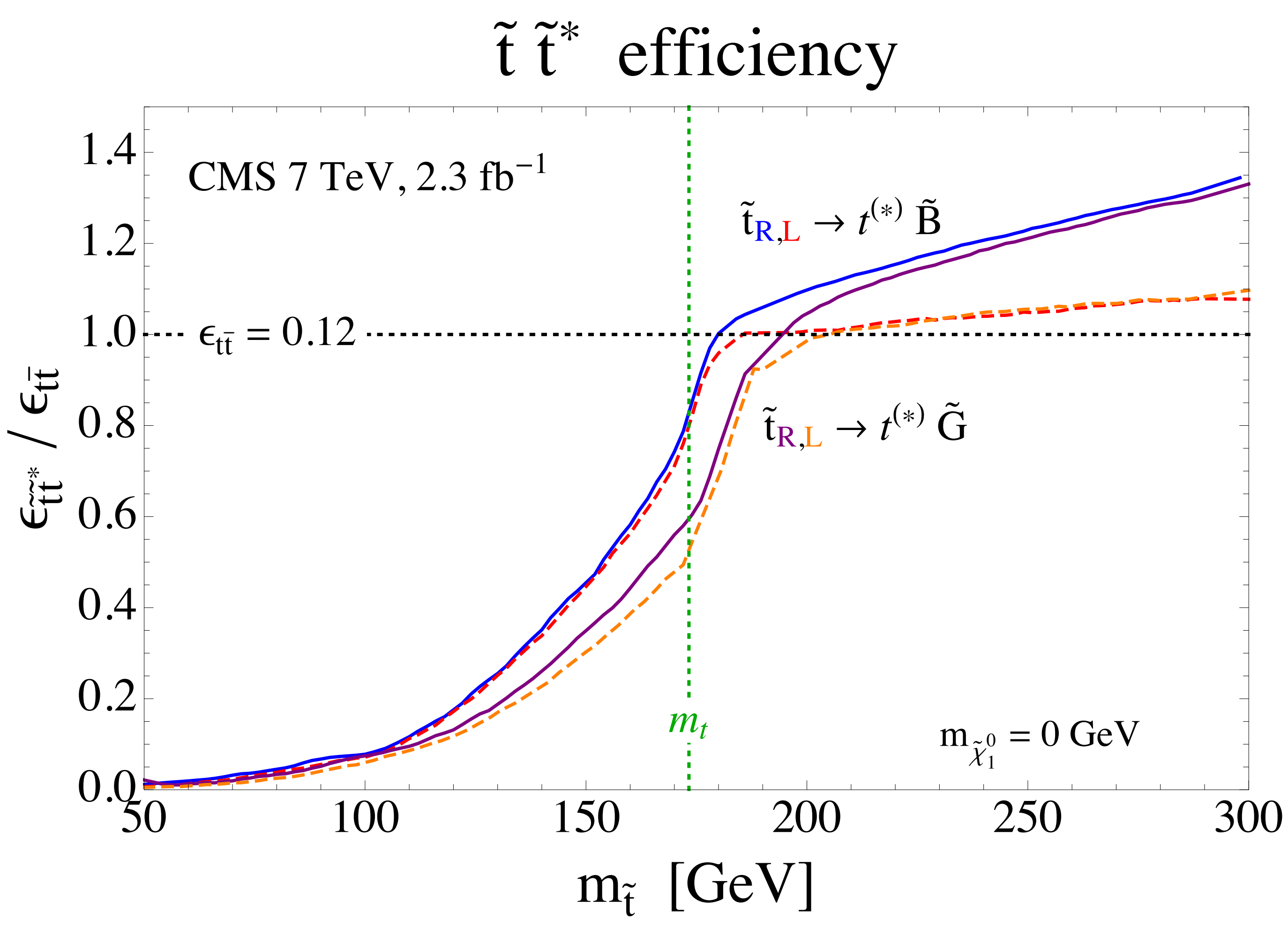




CMS, 1311.3924

Precision Top Cross Section

Czakon, Mitov, Papucci, Ruderman, Weiler 1407.1043

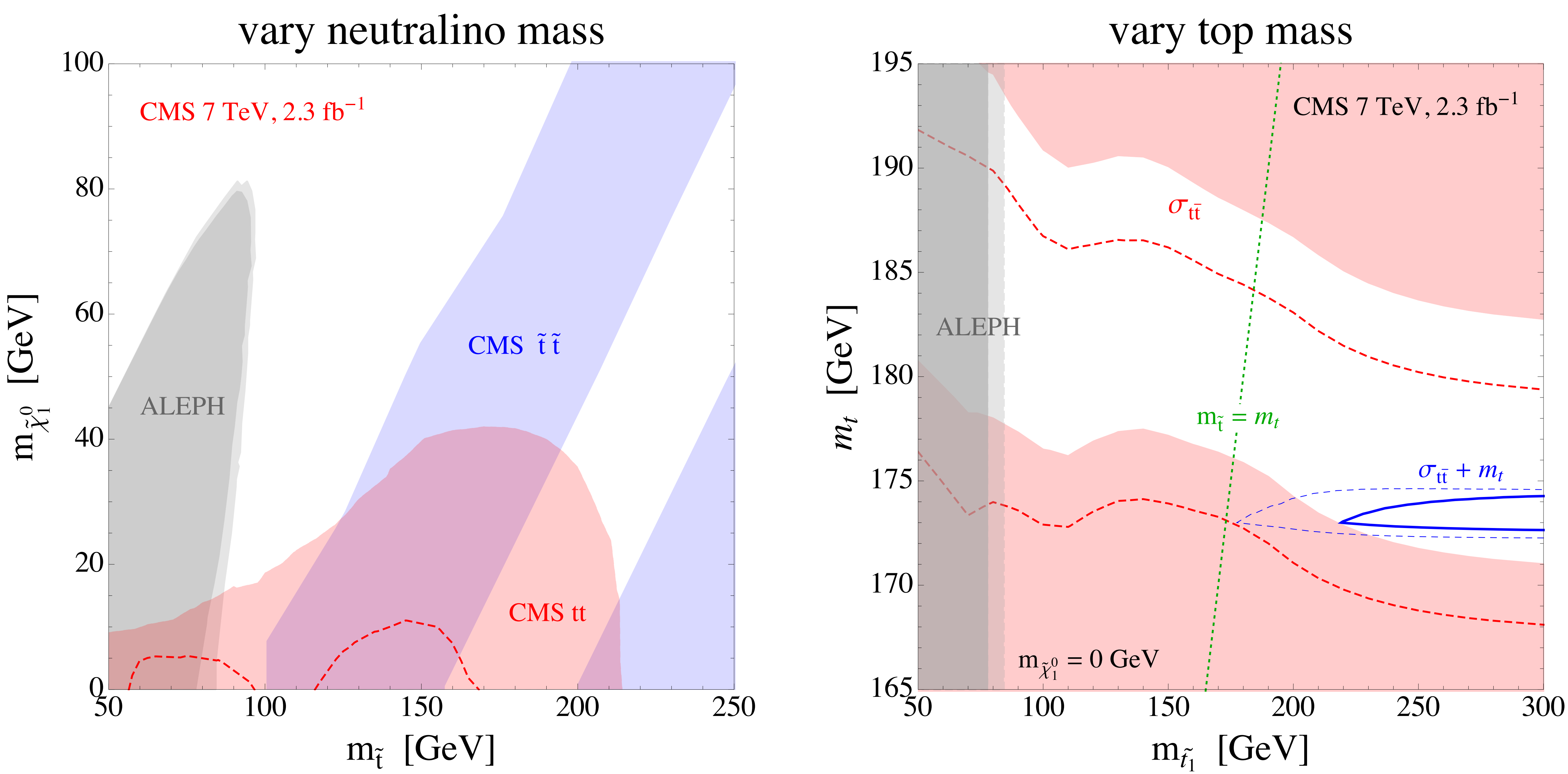


If stops look top-like, why doesn't the top cross section rule them out?

The bottleneck was systematic uncertainty on theory. New NNLO+NNLL (Czakon & Mitov) makes progress possible.

Precision Top Cross Section

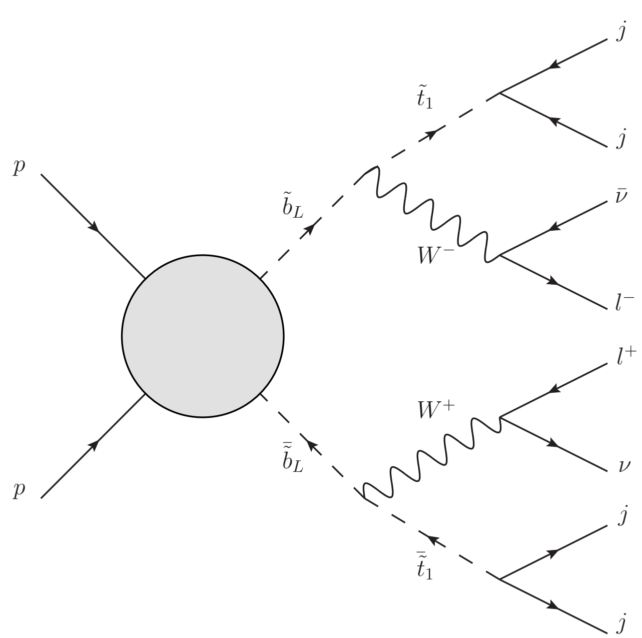
Czakon, Mitov, Papucci, Ruderman, Weiler 1407.1043

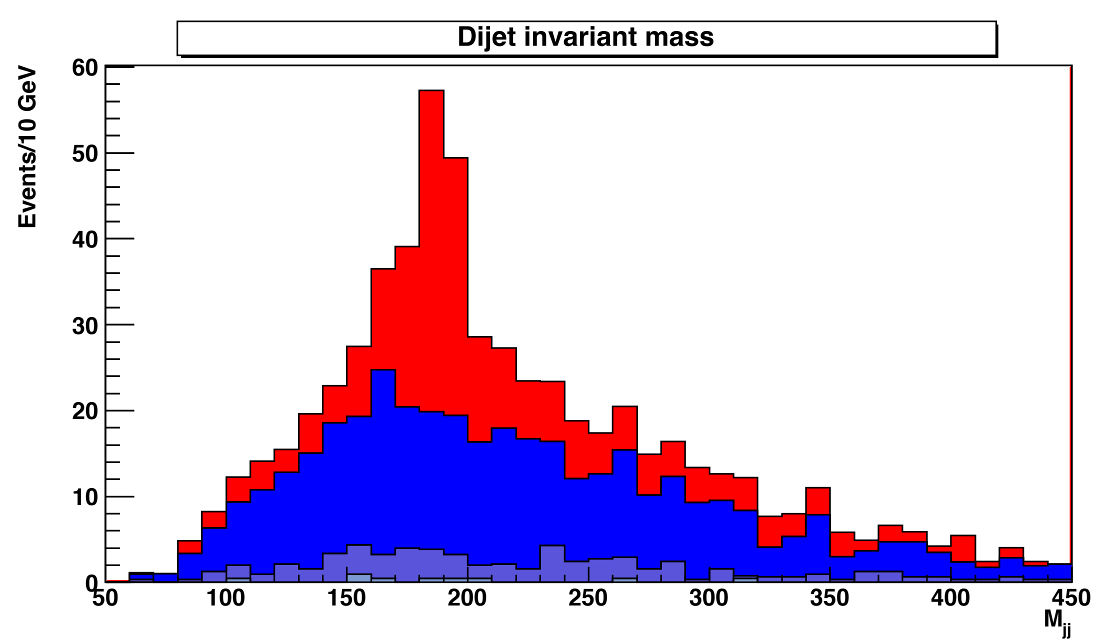


Alternative Stop Decays

It's important to close the "stealthy stop" window for stops near 200 GeV. (See also work in progress of Czakon, Mitov, Papucci, Ruderman, Weiler.)

Another option is that stops decay in a very different way and have been missed. Lots of recent attention on RPV stops, for example Brust, Katz, Sundrum 1206.2353:

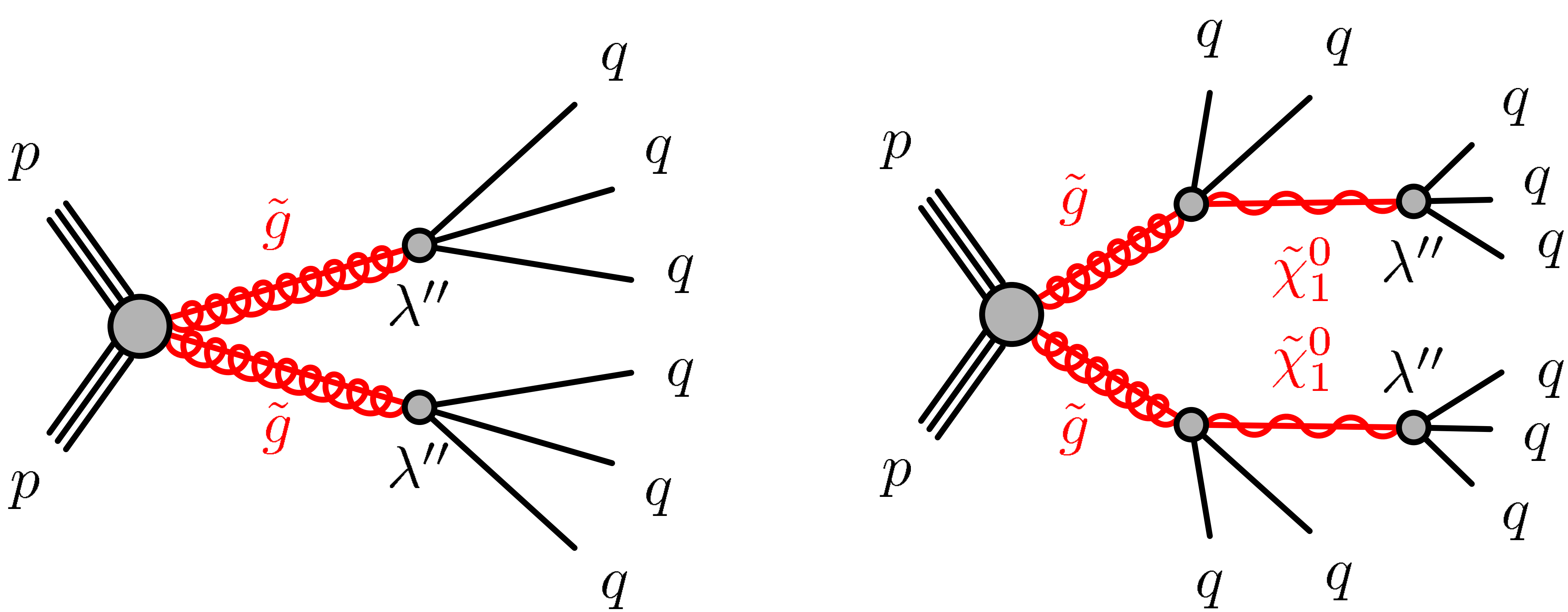




RPV is **Option #1** of many ways to ***hide naturalness***. All energy goes to visible particles.

Gluino Bounds in RPV

Can get events with many hard jets: background is QCD, but QCD usually doesn't share energy among jets so evenly.



(a) 6-quark model (b) 10-quark model

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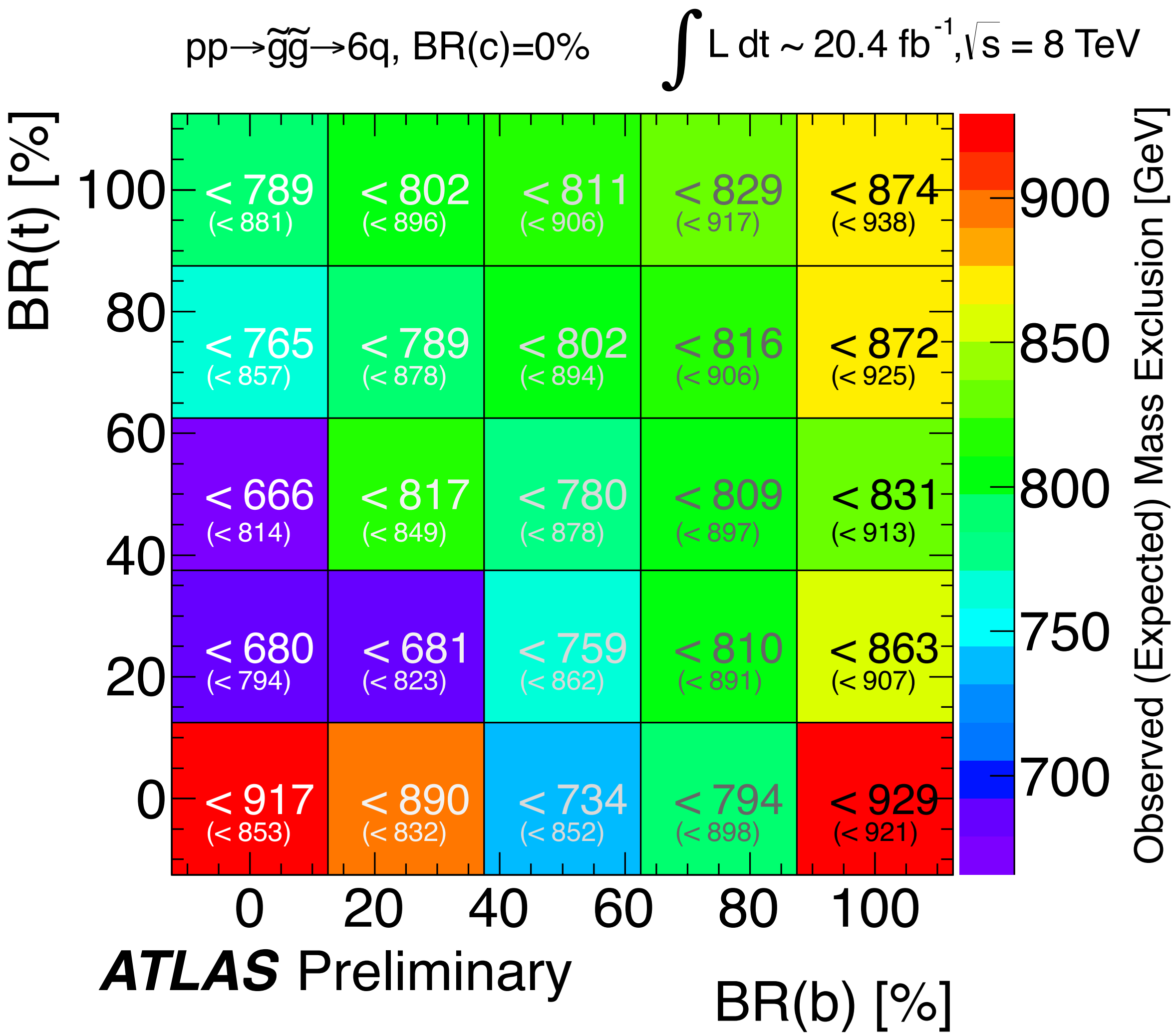
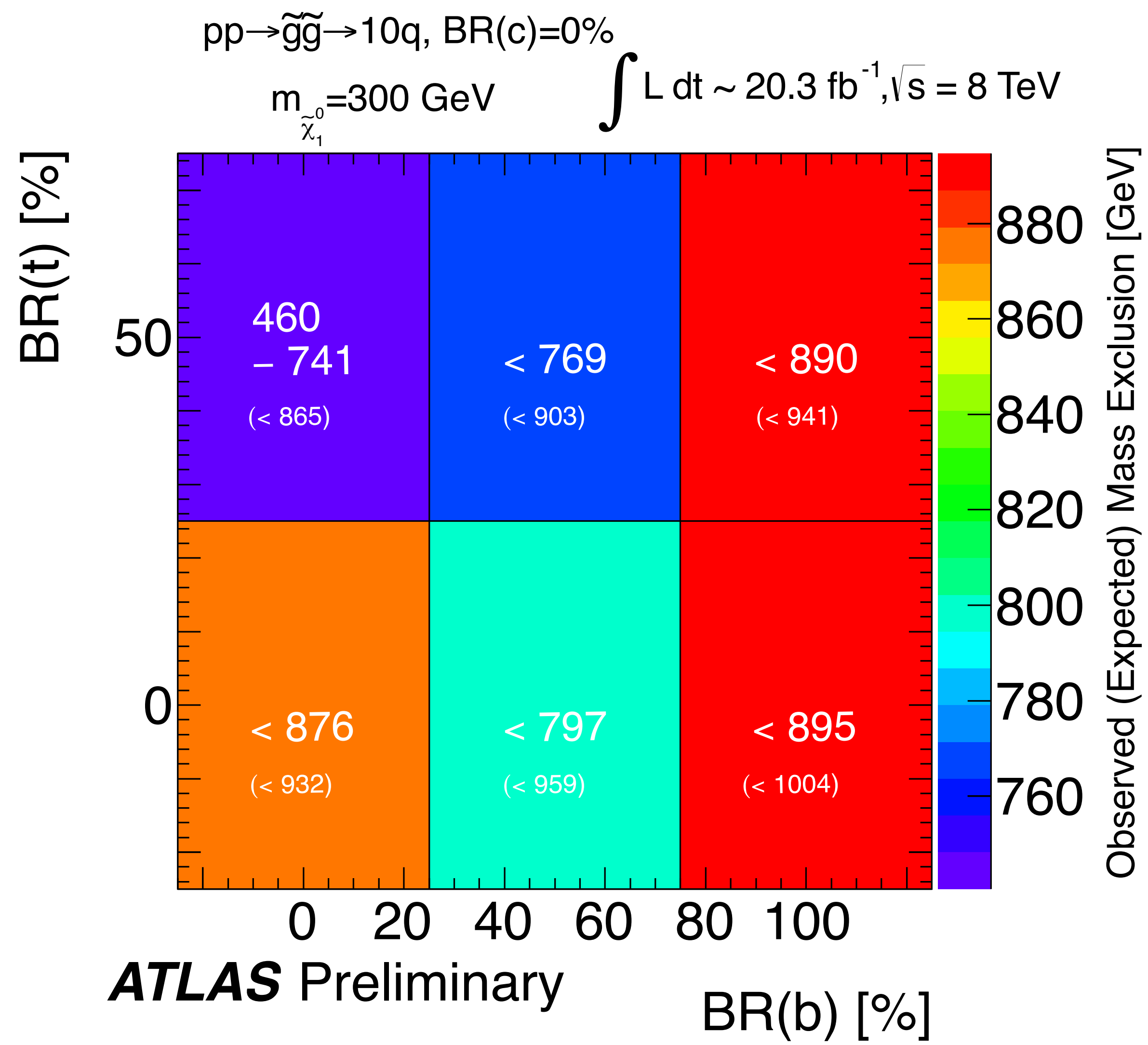
Gluino Bounds in RPV





ATLAS-CONF-2013-091. Exclusions typically ~ 800 GeV.

also see: Evans, Kats, Shih, Strassler 1310.5758

Gluino Bounds in RPV: Same-Sign Dilepton

$$\tilde{g} \to \tilde{t}\bar{t}, \quad \tilde{t} \to \bar{b}\bar{s}$$

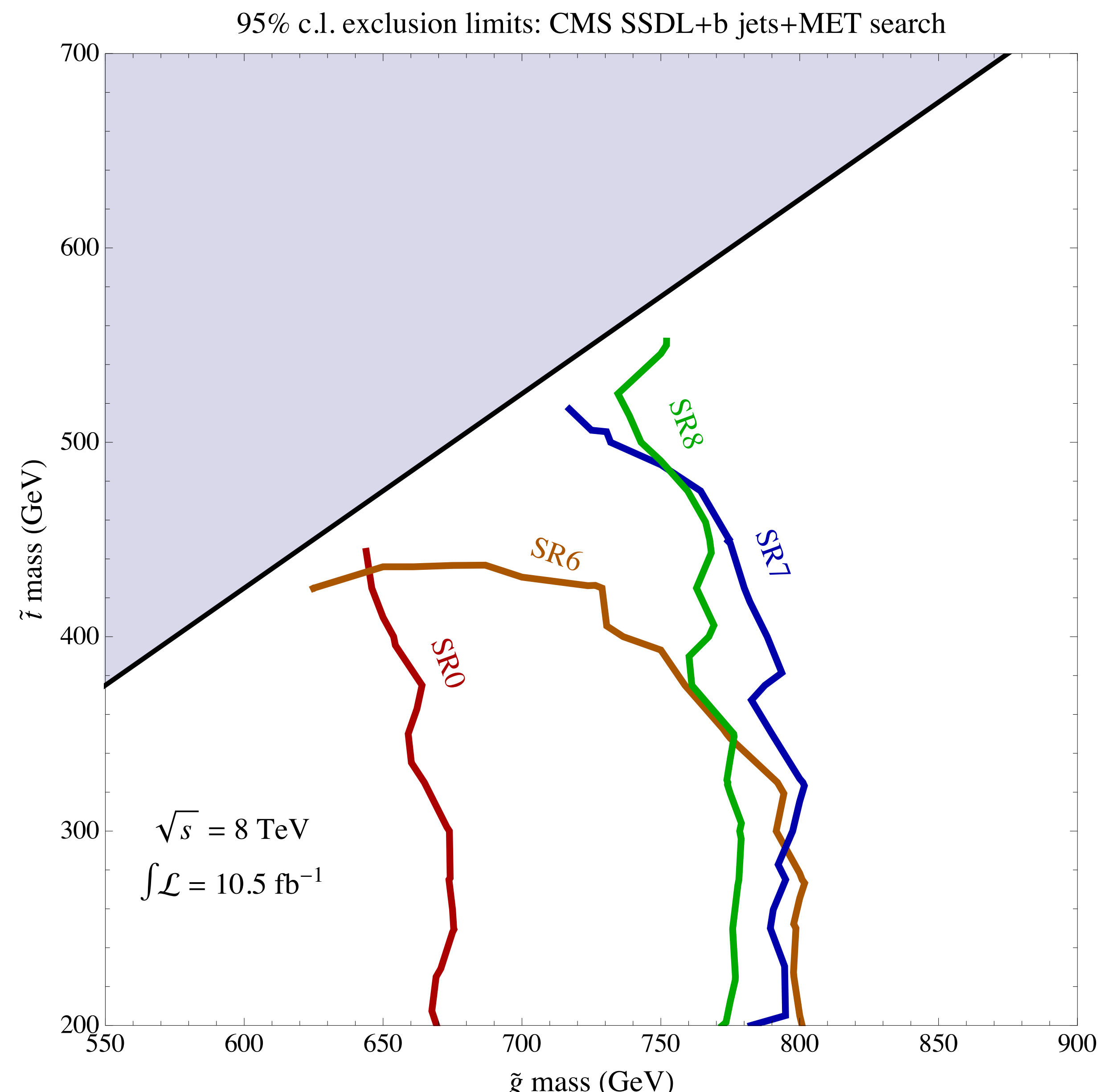
or

$$\tilde{g} \to \tilde{t}^* t, \quad \tilde{t}^* \to bs\,.$$

J. Berger, M. Perelstein, M. Saelim, P. Tanedo 1302.2146

Recasts CMS SSDL+b-jets, 1212.6194. Bounds again ~800 GeV.

It's hard to hide a gluino!

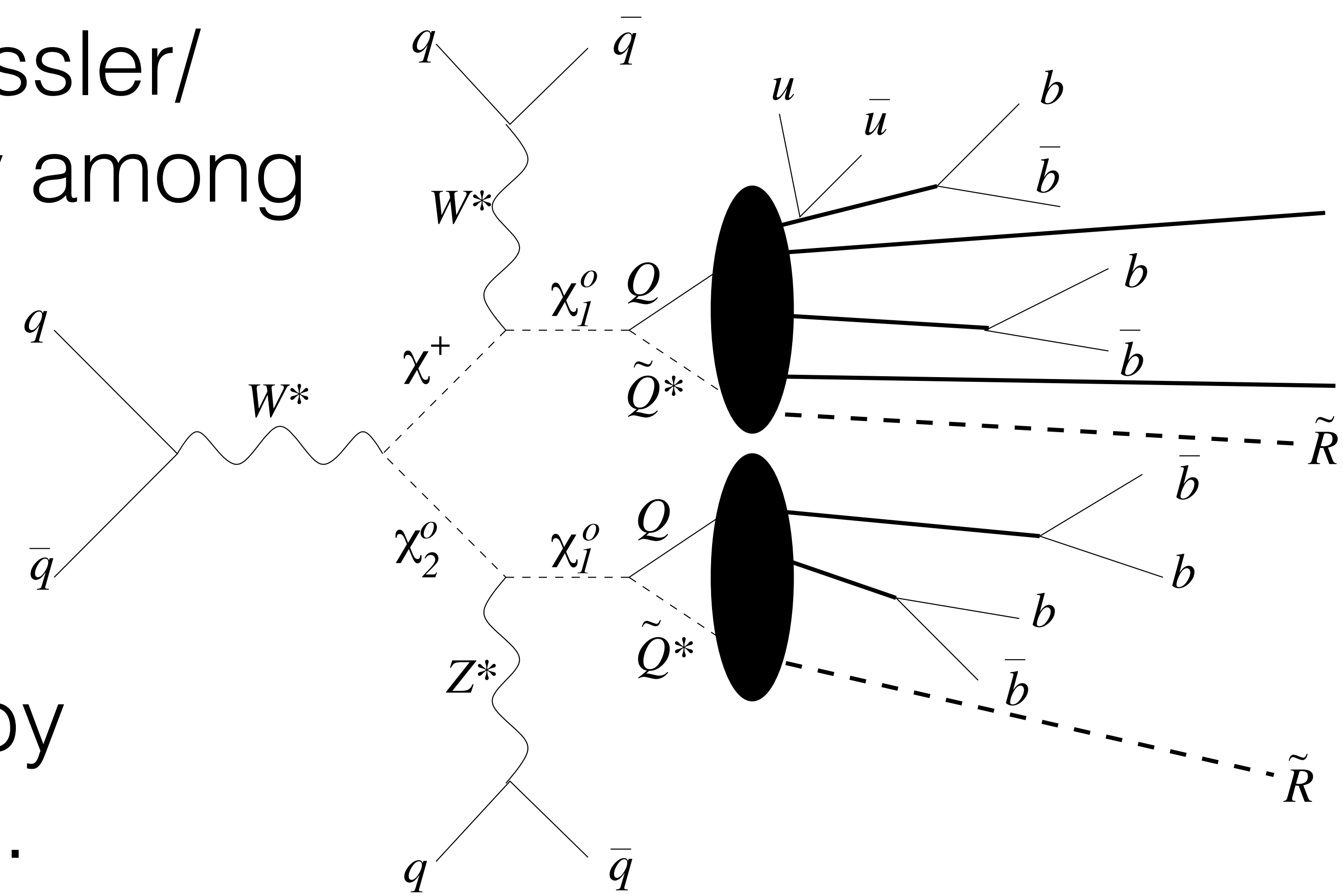


Hiding Naturalness

Option 2: Lengthen decay chains such that missing energy is reduced. **LOSP** “Lightest Ordinary SuperPartner” decays.

“Hidden Valley” (Strassler/Zurek): divide energy among many particles

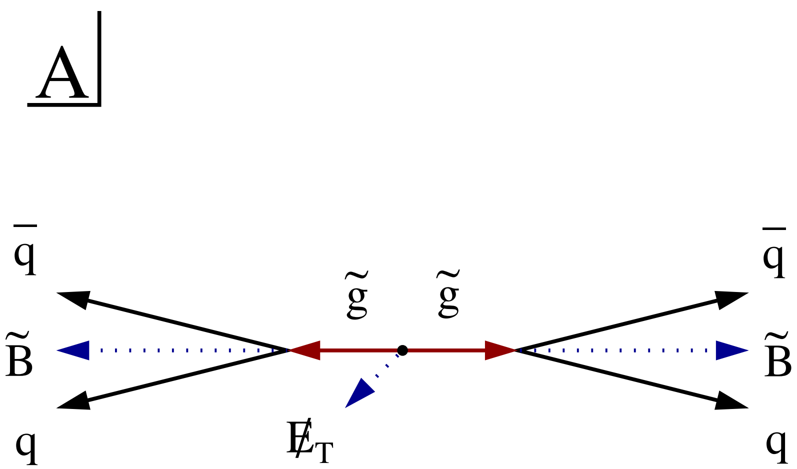
figure from M. Strassler, hep-ph/0607160

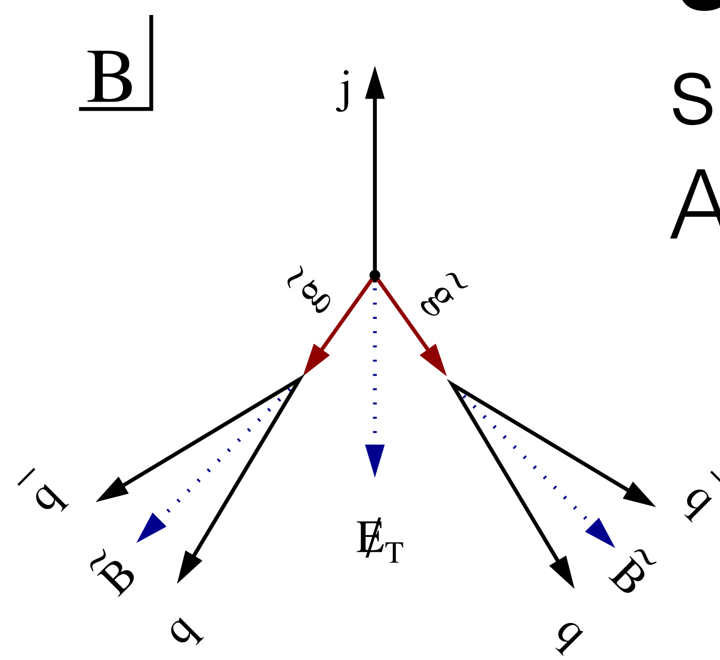


Roughly divide MET by #(final state particles). See also lepton jets, etc.

Hiding Naturalness

Option 3: Adjust masses so there's little phase space for decays.





Compressed SUSY: softer visible particles. A little artificial (tuned).

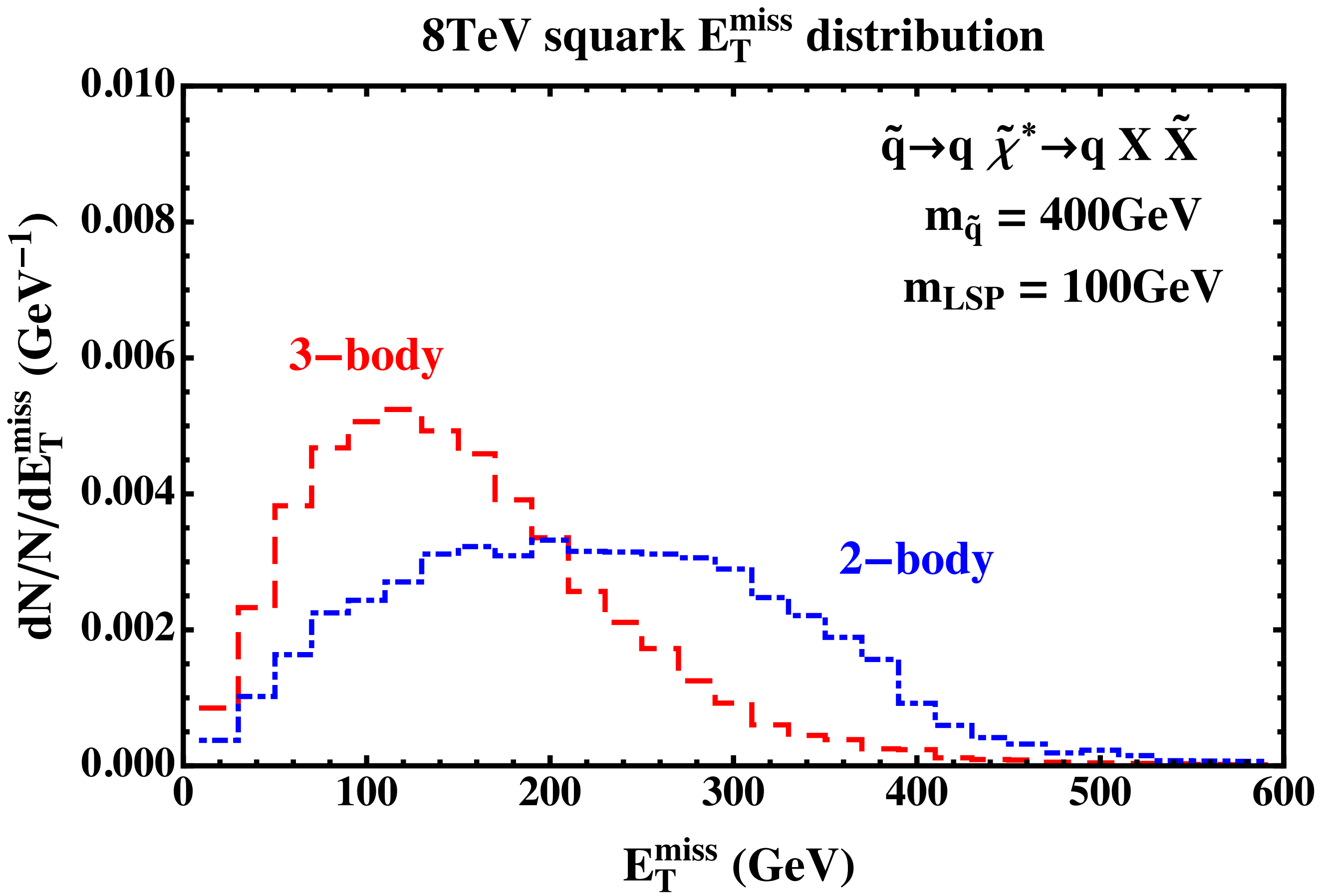
Rely on ISR recoil ("monojet"-like): Alwall, Le, Lisanti, Wacker 0803.0019

A: Can dial MET to 0 by tuning; B: still nonzero MET.

Also see LeCompte & Martin, 1105.4304: compressed spectra.

Hiding Naturalness

Option 4: Decay chains with *more* invisible particles mean *less* visible energy. Need models w/ 3-body decays.

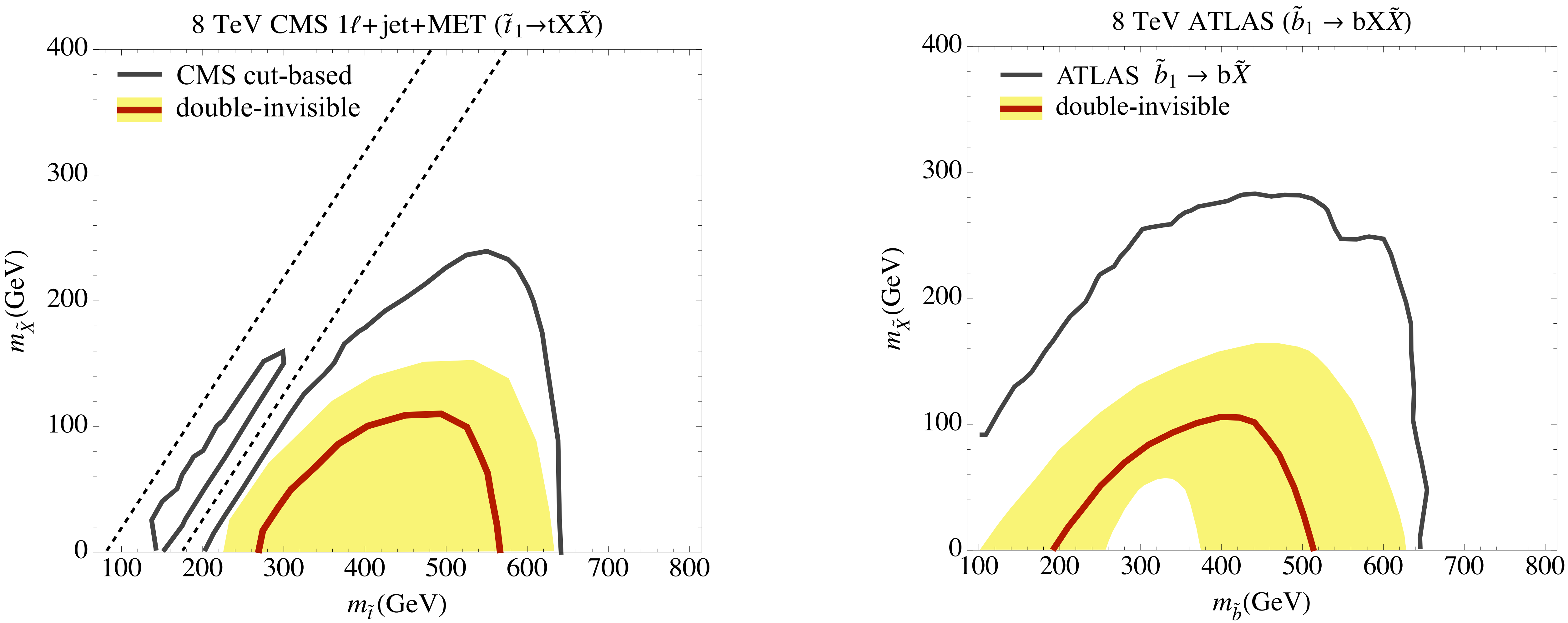


D. Alves, J. Liu, N. Weiner
1312.4965

Like the Hidden Valley case, get an O(1) reduction in MET.

Hiding MET with MET

Increasing the amount of missing energy significantly degrades the reach of current searches.



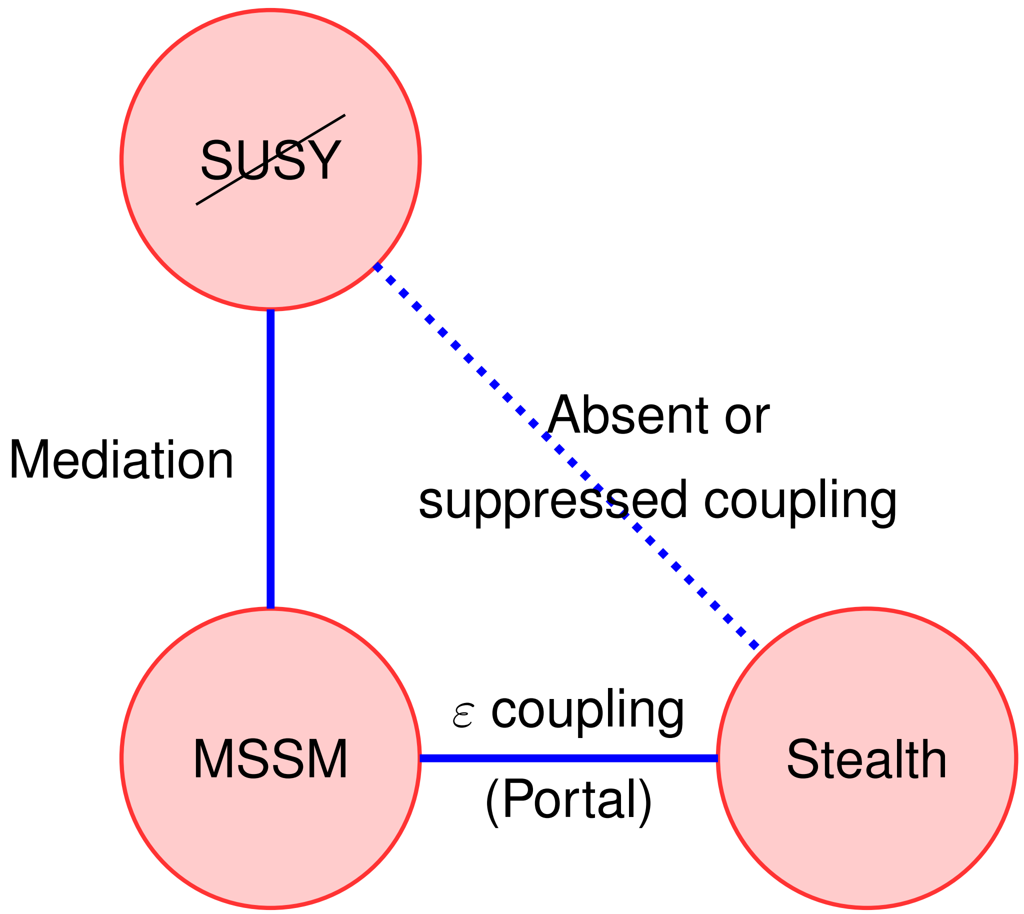
D. Alves, J. Liu, N. Weiner 1312.4965

Models that do this are straightforward to construct.

Stealth Supersymmetry

Option 5:
A ***mechanism*** for suppressing missing ET — ***not tuning it***.

J. Fan, MR, J. Ruderman
1105.5135, 1201.4875



$$M_{\rm SUSY} \sim M_{\rm EWK}$$

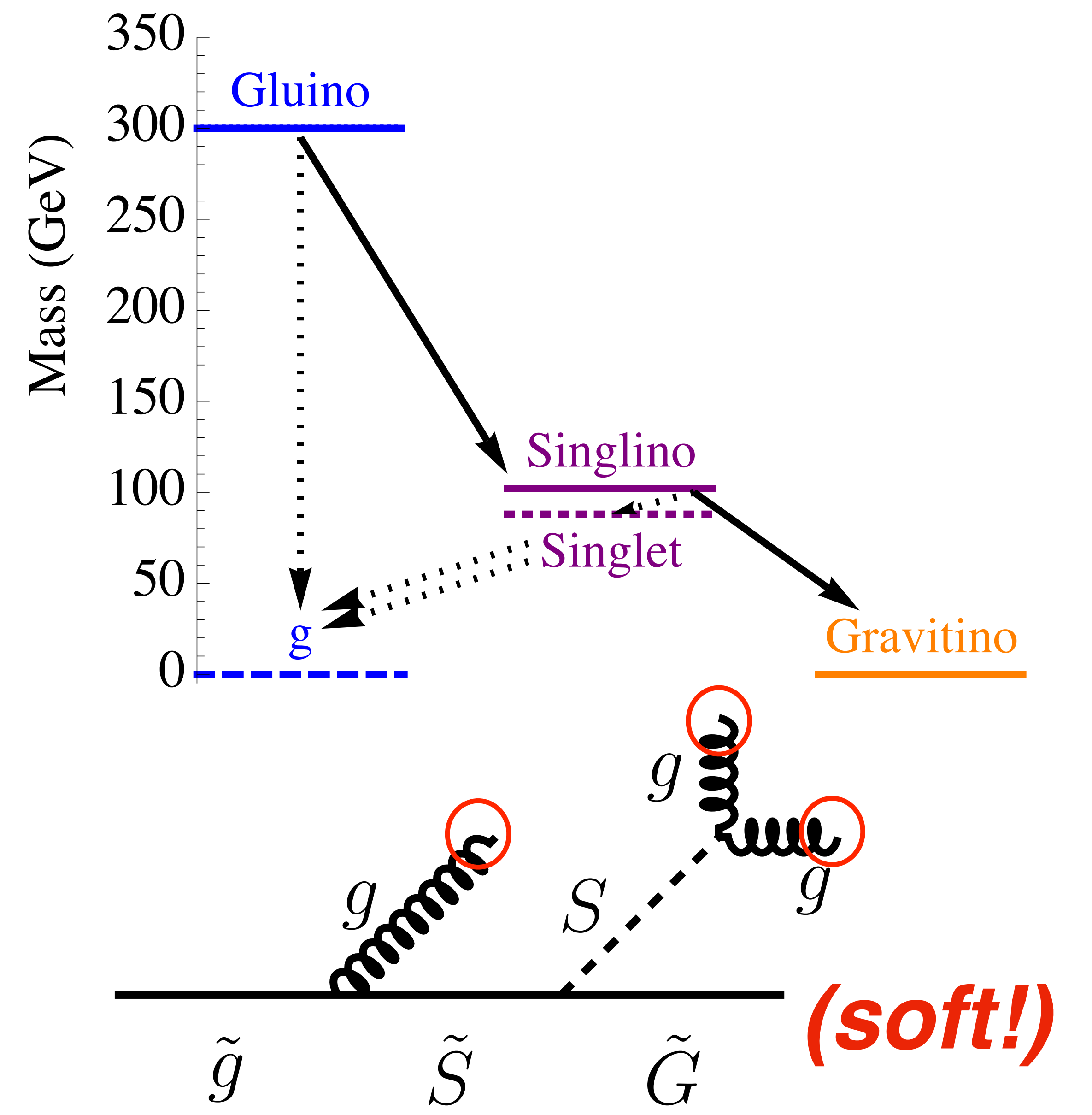
$$M_{\cancel{\rm SUSY}} \sim \varepsilon M_{\rm EWK}$$

Supersymmetry can hide itself!

Have a *parametric* limit: hidden sector SUSY breaking → 0 and missing ET → 0.

Stealth SUSY

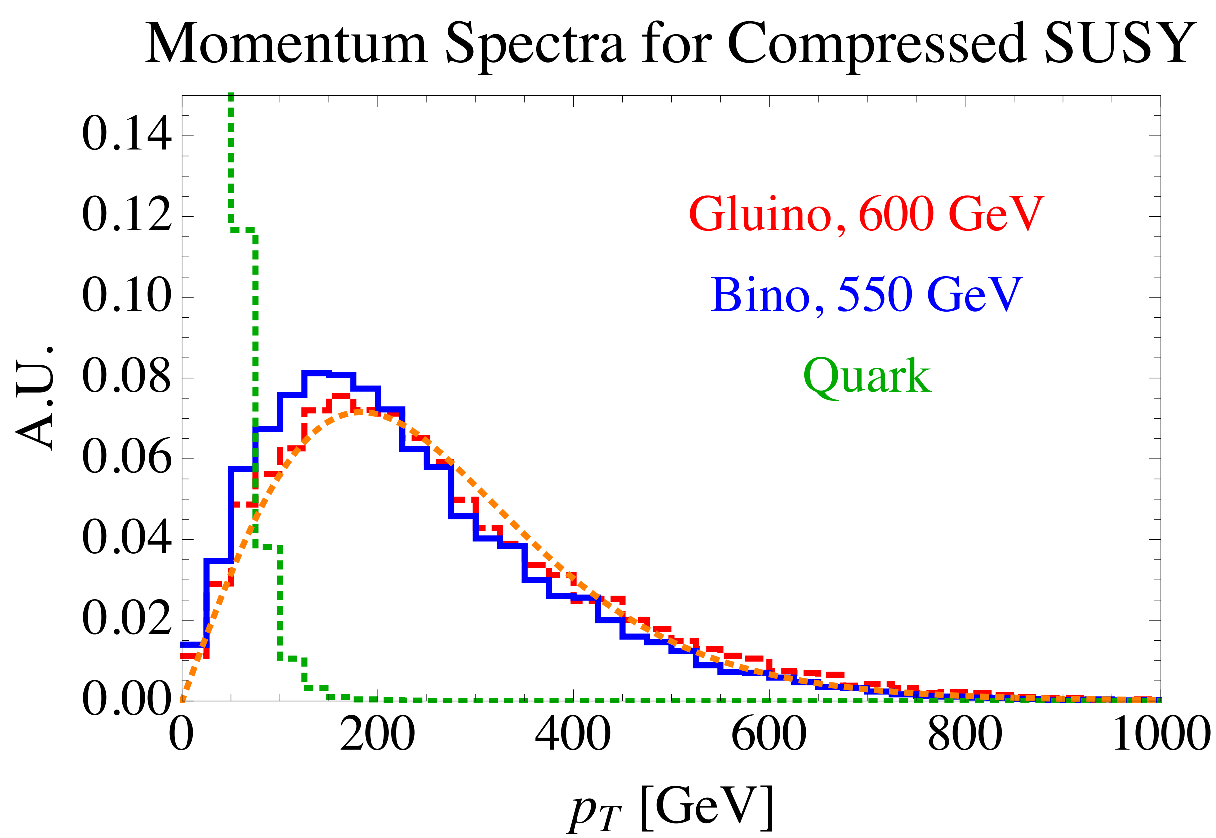
- A nearly-supersymmetric hidden sector (small δm)
- Preserves *R*-parity: lightest visible sector *R*-odd particle ("LOSP") is *forced* to decay to a stealth sector particle.
- *R*-even stealth particles decay back to SM states.



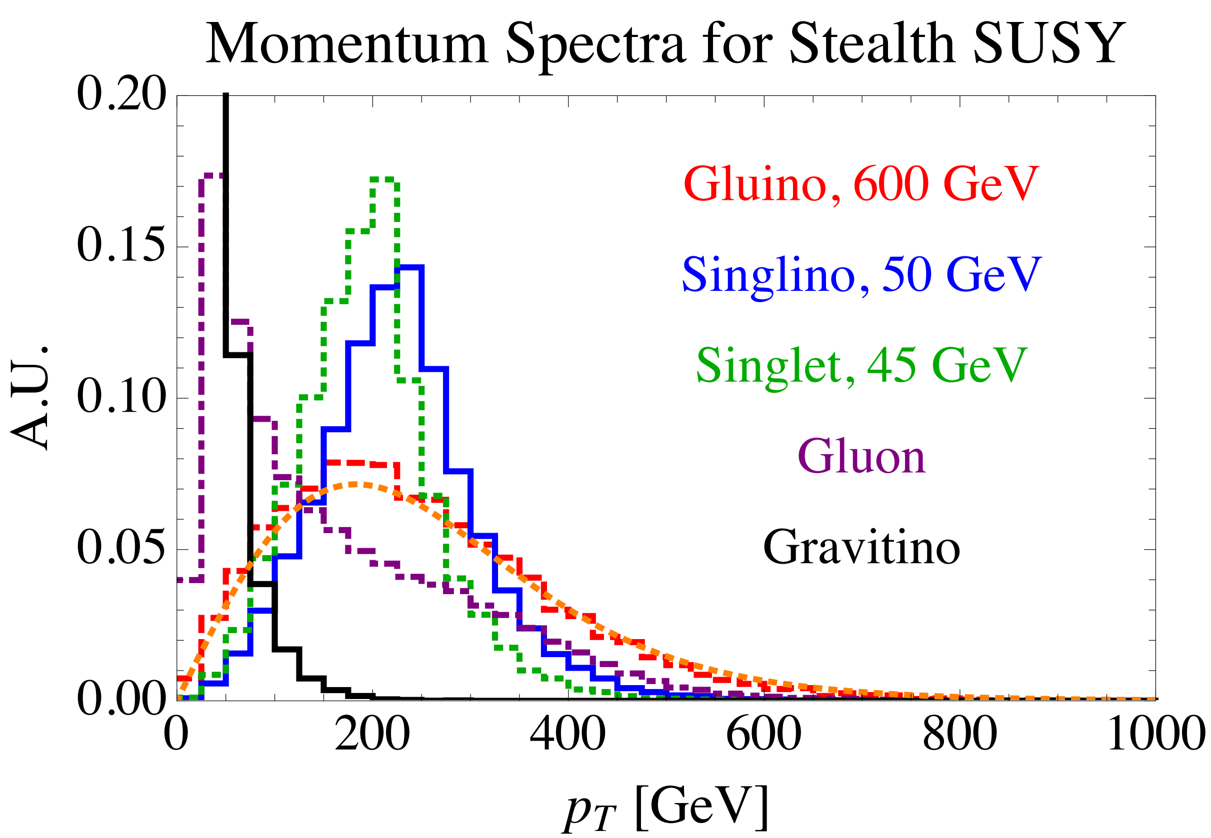
Compressed vs Stealth

In rest frame of decaying particle, all decay products are soft. In the lab frame, *heavy* ones get more momentum. Which are heavy distinguishes **compressed SUSY** from **stealth SUSY**.

(J. Fan, MR, J. Ruderman 1201.4875)



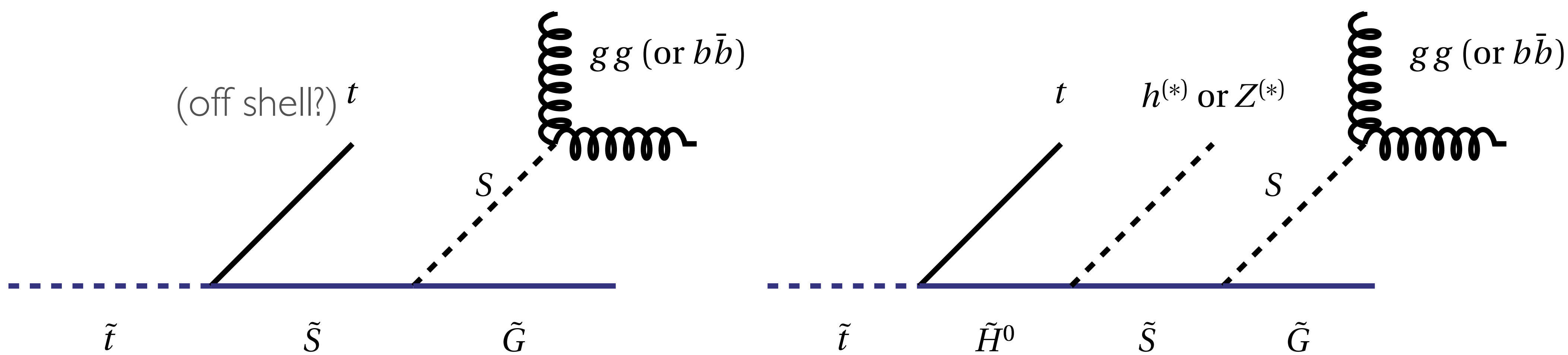
$$\tilde{g} \to q\bar{q}\tilde{B}$$



$$\tilde{g} \to g\tilde{S}, \;\; \tilde{S} \to S\tilde{G}, \text{ and } S \to gg.$$

Natural SUSY?

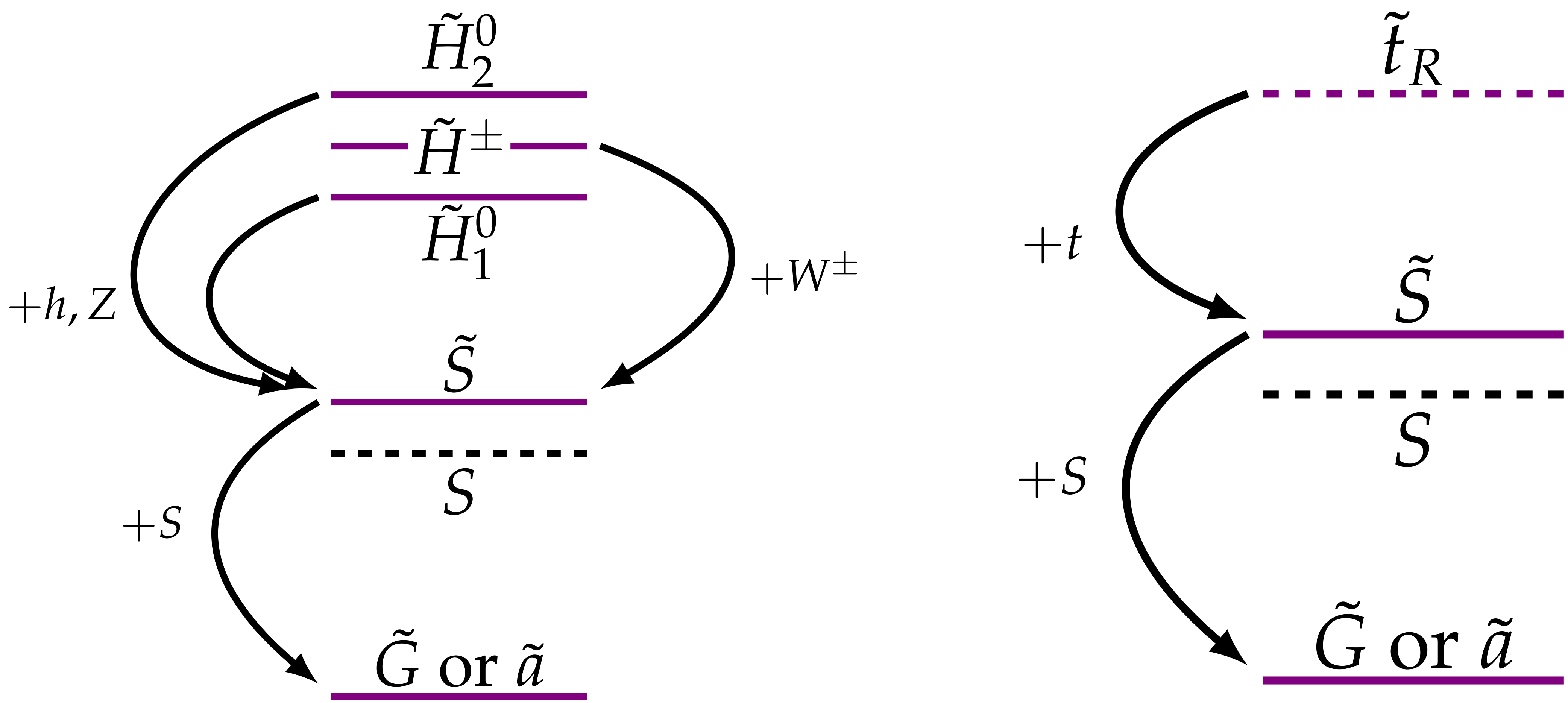
Stealth SUSY gives us a **new set of simplified models** to consider for how a natural stop signal could arise:



It's important to look for these scenarios at the LHC to make sure we're not overlooking an important signal.

Higgsinos may also be in the decay chain for tree-level naturalness.

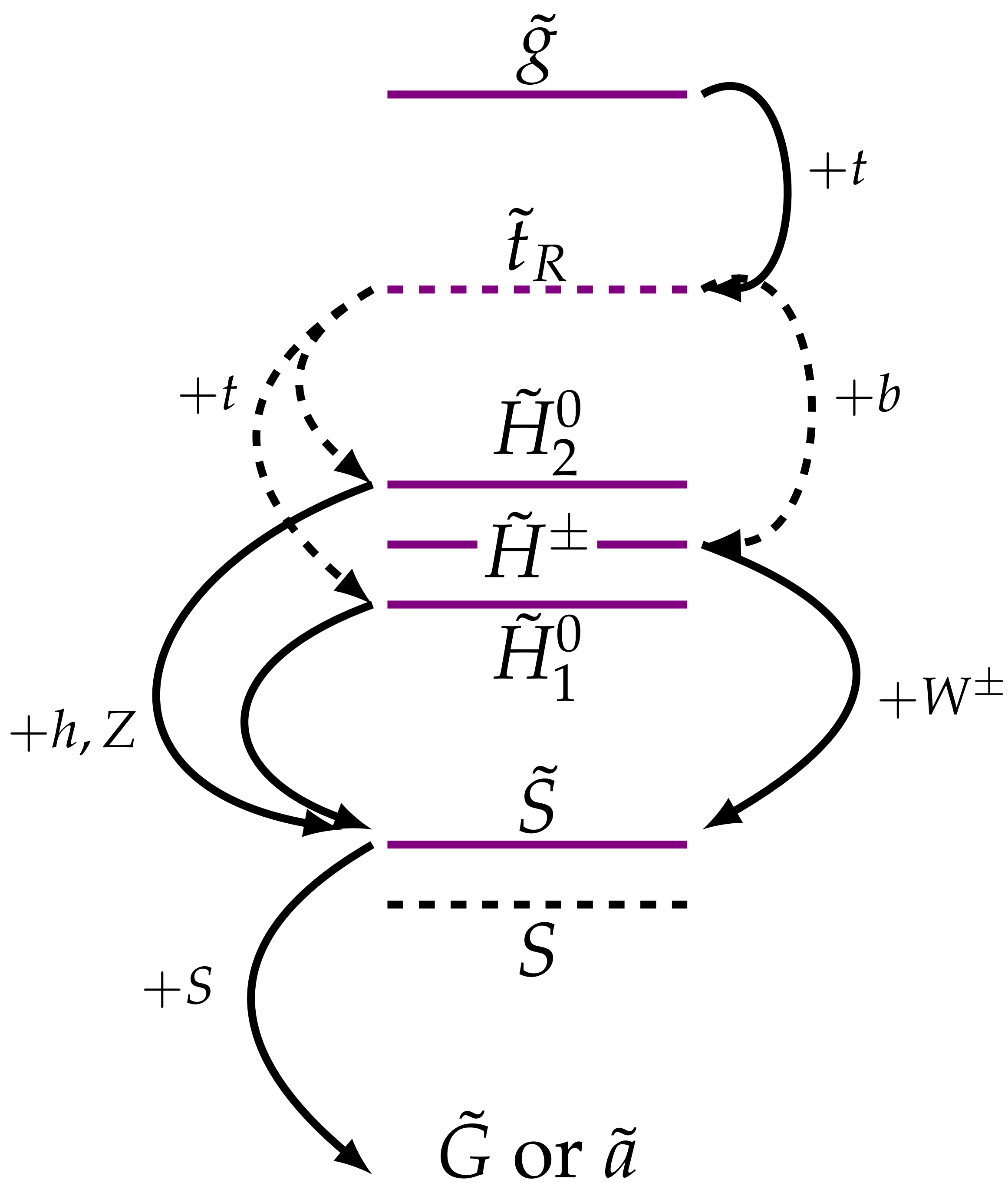
LOSP Decay Chains



LSP: gravitino or axino. Naturally very light.

Not a lot of missing energy, but tops, Higgs bosons, Z bosons: these are not hopeless signals!

Gluino Decay Chains



Simplified model. Scripts compute branching ratios. RH stop decays: roughly half t+neutralino, half b+chargino.

Choices for 2D plots:
- singlino @ 100 GeV,
- singlet @ 90 GeV
- stop halfway between higgsinos and gluino

Easily Implement Simplified Models (Will Make Public)

SLHA Decay Table

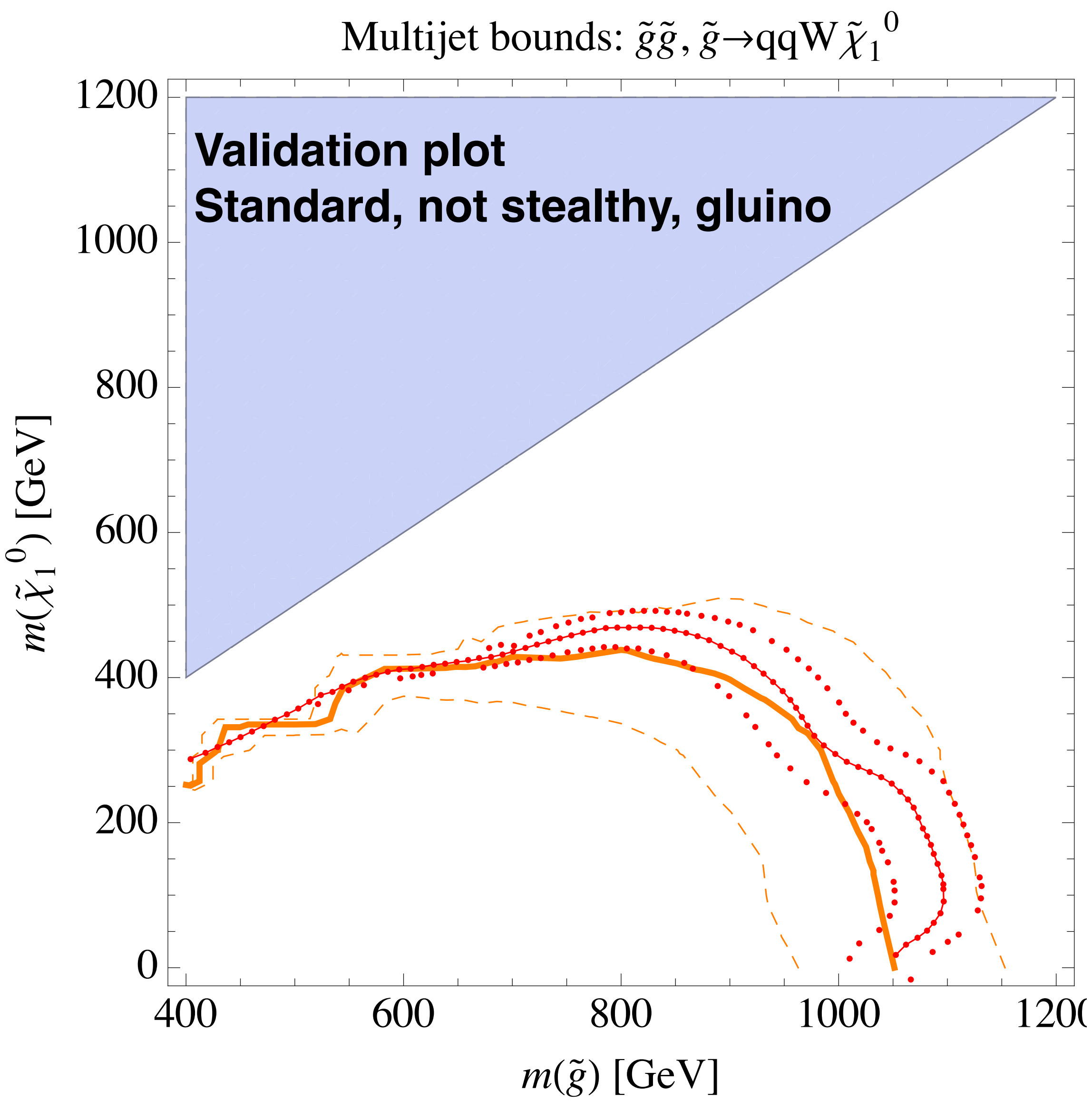
```
BLOCK QNUMBERS 5000001 # singlino singlinobar
    1    0  # 3 times electric charge
    2    2  # number of spin states (2S+1)
    3    1  # colour rep (1: singlet, 3: triplet, 6: sextet, 8: octet)
    4    1  # Particle/Antiparticle distinction (0=own anti)
BLOCK QNUMBERS 5000002 # singlet singletbar
    1    0  # 3 times electric charge
    2    1  # number of spin states (2S+1)
    3    1  # colour rep (1: singlet, 3: triplet, 6: sextet, 8: octet)
    4    1  # Particle/Antiparticle distinction (0=own anti)

BLOCK MASS
#    ID code   pole mass in GeV
     5000001   100.0  # m(singlino)
     5000002   90.0   # m(singlet)
     1000022   1.0    # m(axino)
     1000006   562.5  # m(stop)
     1000021   925.0  # m(gluino)
     1000023   200.0  # m(chi0_1)
     1000025   200.0  # m(chi0_2)
     1000024   200.0  # m(chi+_1)

#       ID          Width
DECAY   1000006     1.00000000E+00   # t1 decays
    2.16000432E-01   2    1000023     6     # BR(t1 -> chi0_1 t)
    2.16000432E-01   2    1000025     6     # BR(t1 -> chi0_2 t)
    5.67999136E-01   2    1000024     5     # BR(t1 -> chi+_1 b)
#       ID          Width
DECAY   1000021     1.00000000E+00   # gluino decays
    5.00000000E-01   2   -1000006     6     # BR(gluino -> t t1~)
    5.00000000E-01   2    1000006    -6     # BR(gluino -> t~ t1)
#       ID          Width
DECAY   1000023     1.00000000E-04   # chi0_1 decays
    1.00000000E+00   2    5000001     23    # BR(chi0_1 -> Z singlino)
    0.00000000E+00   2    5000001     25    # BR(chi0_1 -> h singlino)
#       ID          Width
DECAY   1000025     1.00000000E-04   # chi0_2 decays
    1.00000000E+00   2    5000001     23    # BR(chi0_2 -> Z singlino)
    0.00000000E+00   2    5000001     25    # BR(chi0_2 -> h singlino)
#       ID          Width
DECAY   1000024     1.00000000E-04   # chi+_1 decays
    1.00000000E-00   2    5000001     24    # BR(chi+_1 -> w+ singlino)
#       ID          Width
DECAY   5000001     1.00000000E-03   # singlino decays
#          BR         NDA     ID1      ID2
    1.00000000E-00   2    5000002   1000022     # BR(singlino -> singlet axino)
#       ID          Width
DECAY   5000002     1.00000000E-03   # singlet decays
#          BR         NDA     ID1      ID2
    1.00000000E-00   2       5       -5     # BR(singlet -> b b~)
```

Feed to Pythia with LHE gluino or stop pairs; it does the rest

```
// Generator
Pythia pythia;

pythia.readString("PartonLevel:ISR = on");
pythia.readString("PartonLevel:FSR = on");
pythia.readString("PartonLevel:MPI = on");
pythia.readString("HadronLevel:Hadronize = on");

// SLHA file
pythia.readString("SLHA:readFrom = 2");
pythia.readString("SLHA:file = " + slhafile);
pythia.readString("SLHA:useDecayTable = true");

// Initialize LHE file run
pythia.readString("Beams:frameType = 4");
pythia.readString("Beams:LHEF = " + lhefile);
```

Stealth SUSY Bounds

Work in progress with JiJi Fan, Rebecca Krall, David Pinner, Josh Ruderman: how much of natural stealthy SUSY survives?



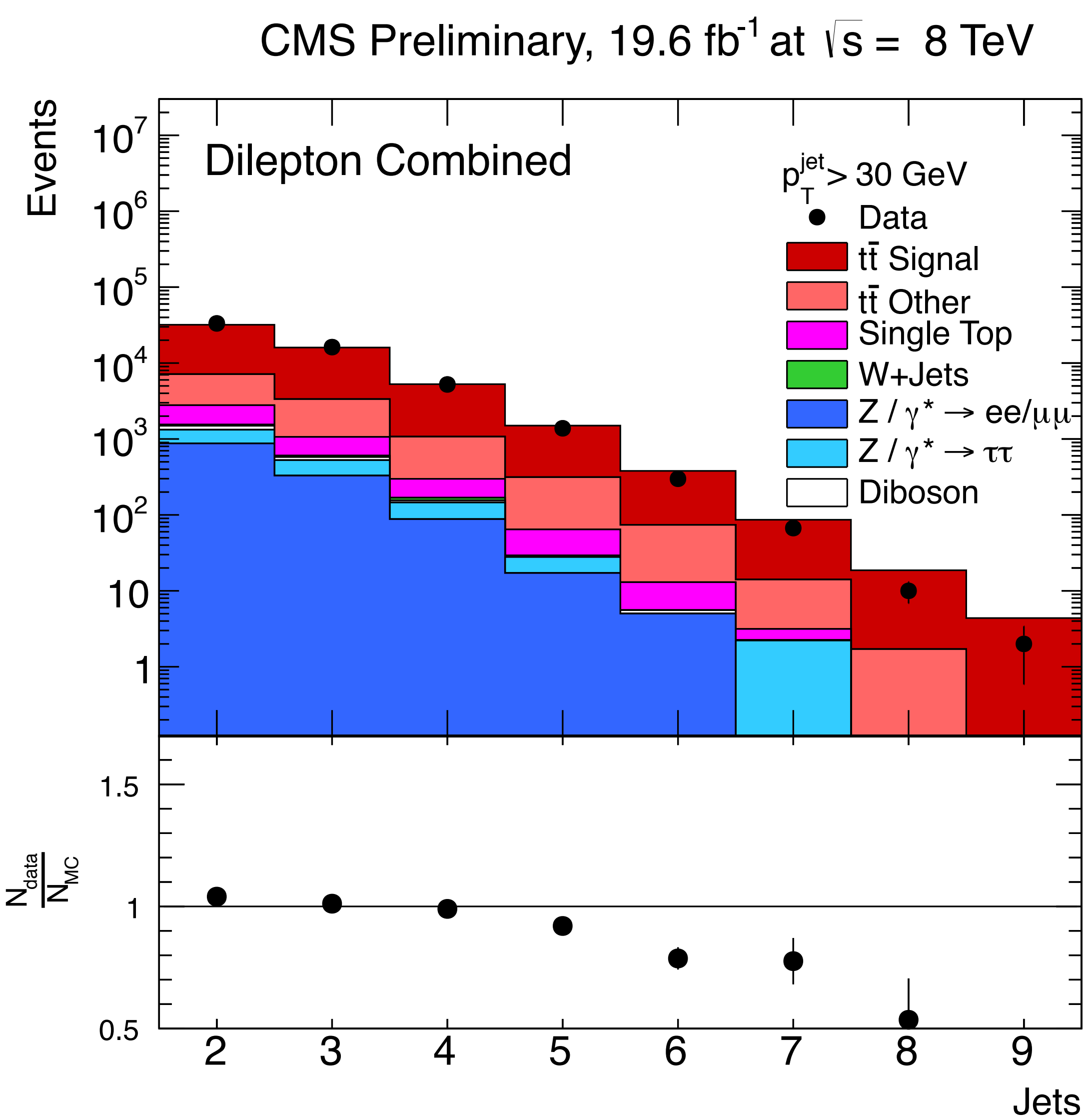
Determining this requires "recasting": coding up searches and making validation plots like the one at left. (ATLAS 1308.1841)

Also using Drees et al. "CheckMATE" recasting tool (1312.2591).

Not many complete results to show you so far.

Toward Stealth SUSY Stop Bounds

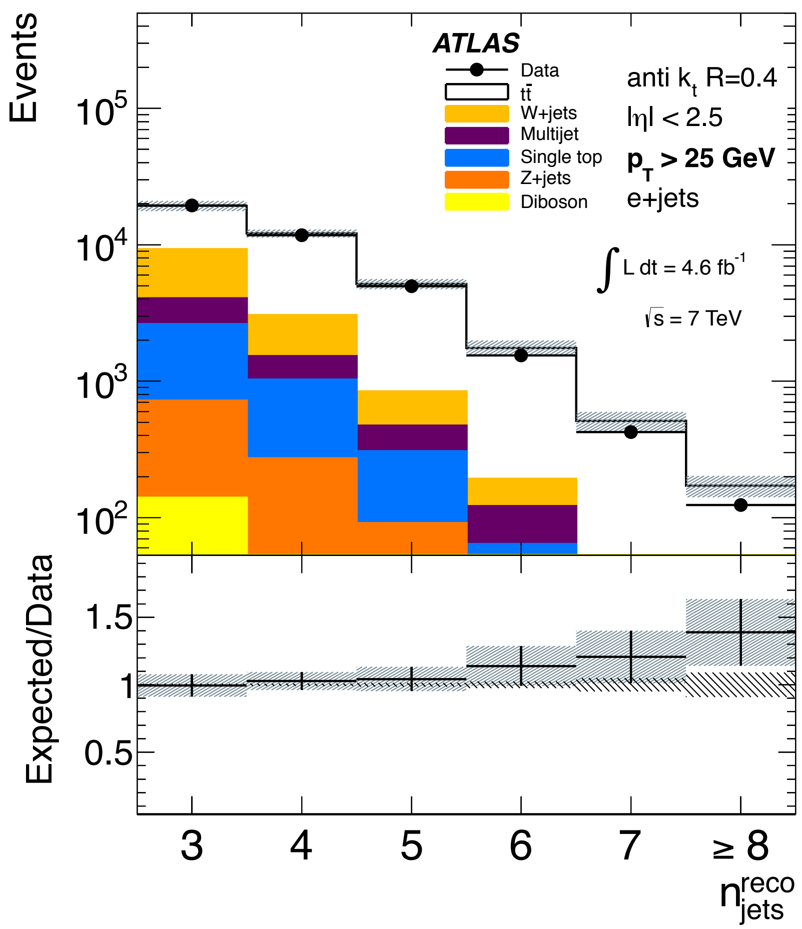
Preliminarily, some regions of gluino parameter space are ruled out, but direct stop production in these simplified models is hard to bound with current searches.



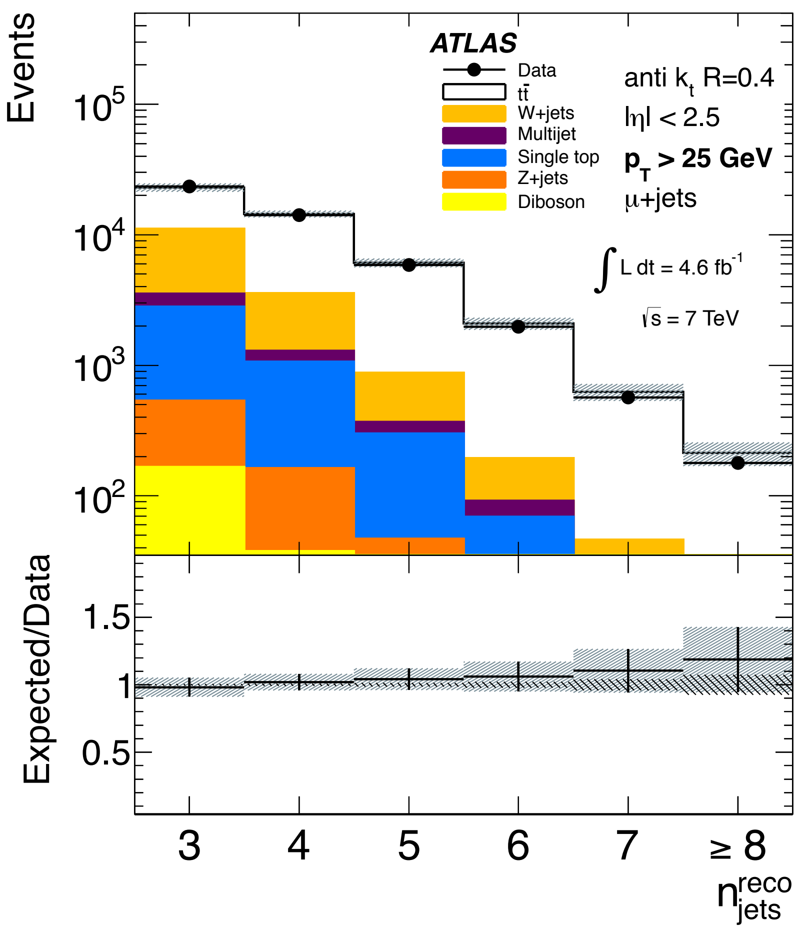
Direct stop bounds might come from jet counts in top events (e.g. this plot from CMS PAS TOP-12-041). But background values are iffy in the 8 or 9 jet bin. What's the right error bar?

Would like to see direct searches for top events with dijet resonance peaks!

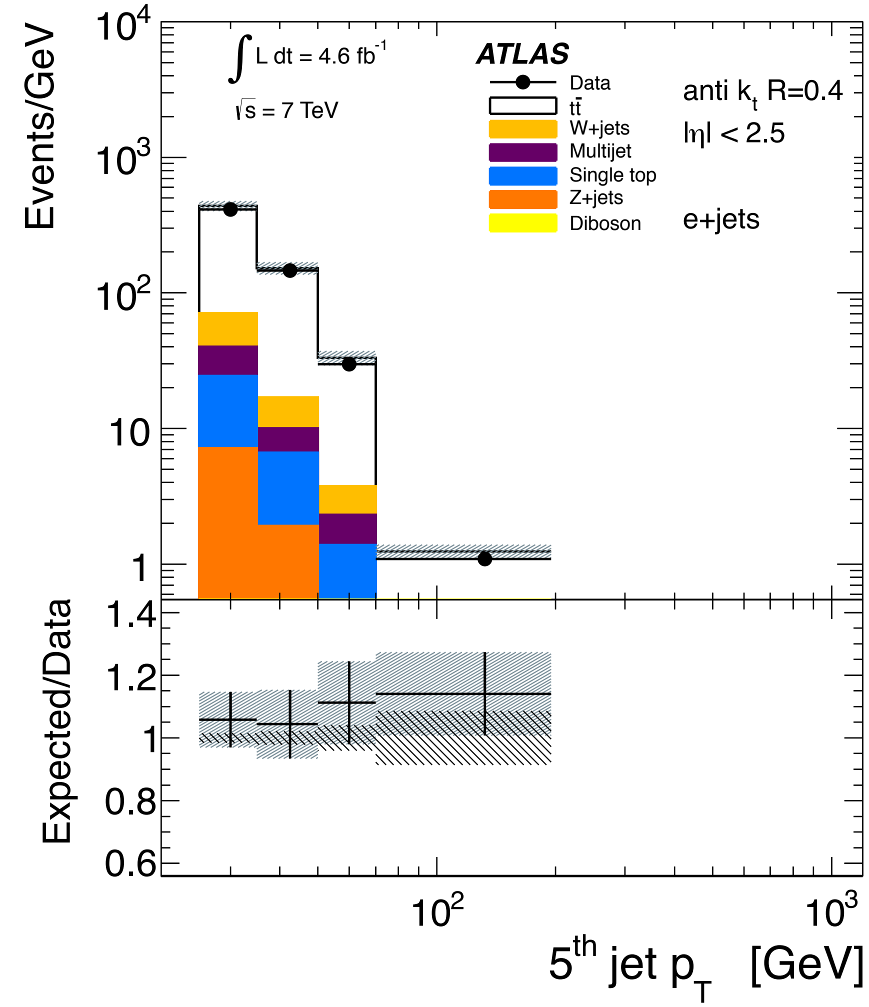
Toward Stealth SUSY Stop Bounds



(a) $e + \text{jets}$, $p_T > 25$ GeV



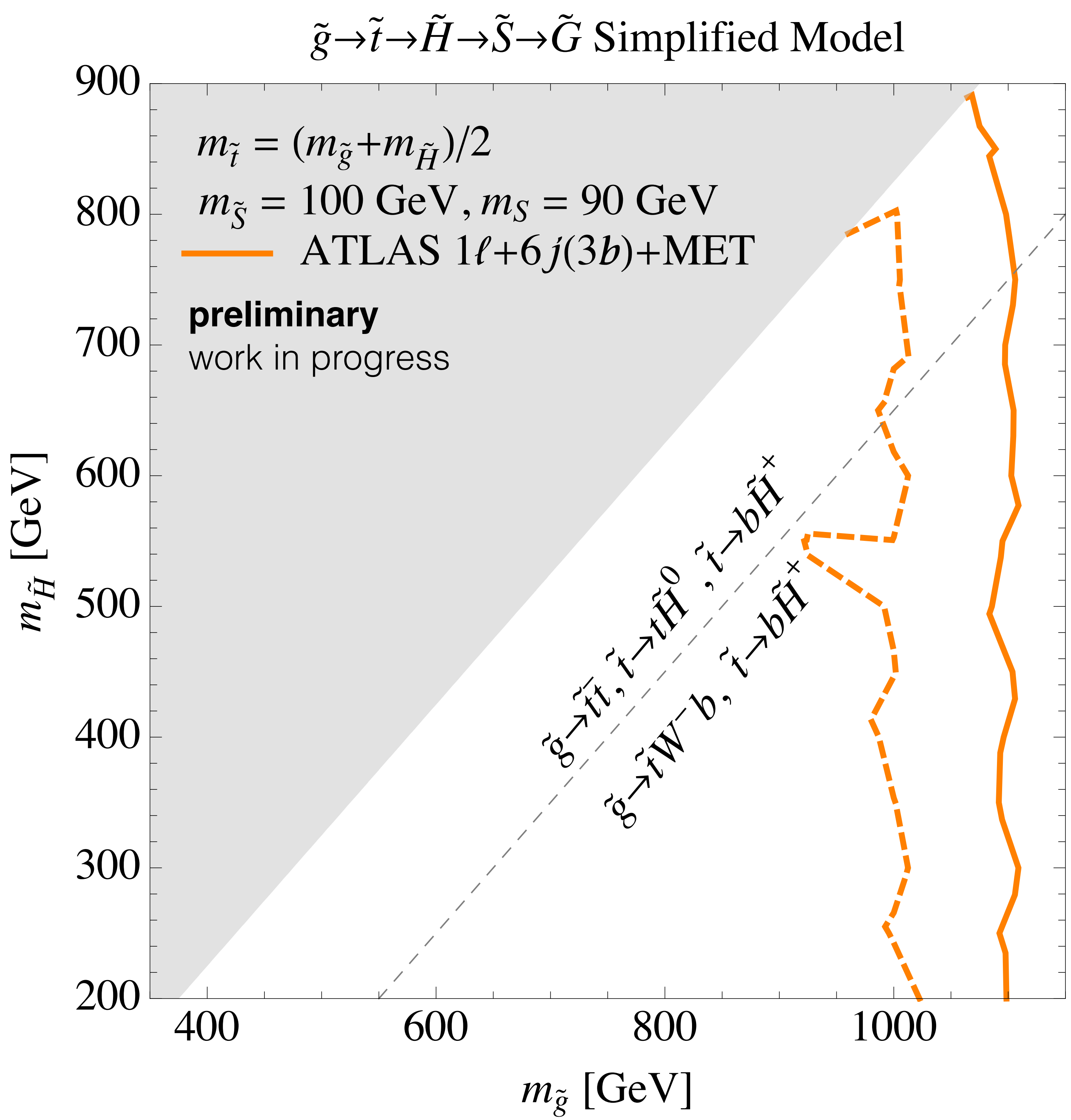
(b) $\mu + \text{jets}$, $p_T > 25$ GeV



(b) $e + \text{jets}$, $p_T > 25$ GeV, 5th jet

ATLAS 1407.0891: jet multiplicity & p_T distributions in top pair production look very SM-like. Can use to bound new physics.

Stealth Gluino Constraints



Lots of *W* bosons: leptons and MET.

Ruled out to above 1 TeV! (Solid line: estimated exclusion; dashed line: conservative estimate by a factor of 2.)

ATLAS CONF 2013-061 Search with 3 b-jets

Lessons

Stops and higgsinos can still be hiding due to relatively small cross sections.

Gluinos are very hard to hide! Bounds typically near 1 TeV even for "hidden" scenarios. **Gluino reach will improve rapidly with 13 TeV data.**

The gluino bound already puts some strain on naturalness, but it's important to fill the gaps. **Stops could already be produced and hiding in data**. Look for a wider range of decays!

Many Roads to Naturalness

- Stops: RPV, stealth, "just around the corner"?
- Higgsinos: crucial for tree-level naturalness. But very hard to see directly if LSP. (Soft leptons + ISR jets or WBF?)
- Gluinos: key for two-loop naturalness, and are easy to see (even in RPV). None so far. Should show up at 13 TeV or…?
- Heavy Higgses: matter for tree-level naturalness. Can be decoupled at large tan beta, but very large tan beta is disfavored by $b \to s\gamma$ in natural theories. Not often discussed as a SUSY naturalness signature, but important!

Suggested Strategy

"Natural SUSY" often means a particular set of theories or simplified models: light stops and higgsinos, other squarks heavy, stable LSP. Signals involve missing energy.

But many different theories can be natural.

We should aim to have a **catalogue of "natural SUSY simplified models"** capturing the **diverse possible signals**. Stealth SUSY, RPV, "Hiding MET with MET," etc.

In Run 2, attention should be given to these nonminimal models: if we're going to rule out (or find!) naturalness, important not to have too strong a theory bias.

Summary

- LHC Run 1 has put some strain on naturalness
- Important to keep looking in the hiding places: squeezed regions; R-parity violation; decays with multiple invisible particles (“hiding MET with MET”); Stealth Supersymmetry models; Hidden Valleys; long lifetimes, displaced vertices
- Would be good to see a suite of these “hidden natural SUSY” simplified models constrained in CMS and ATLAS publications

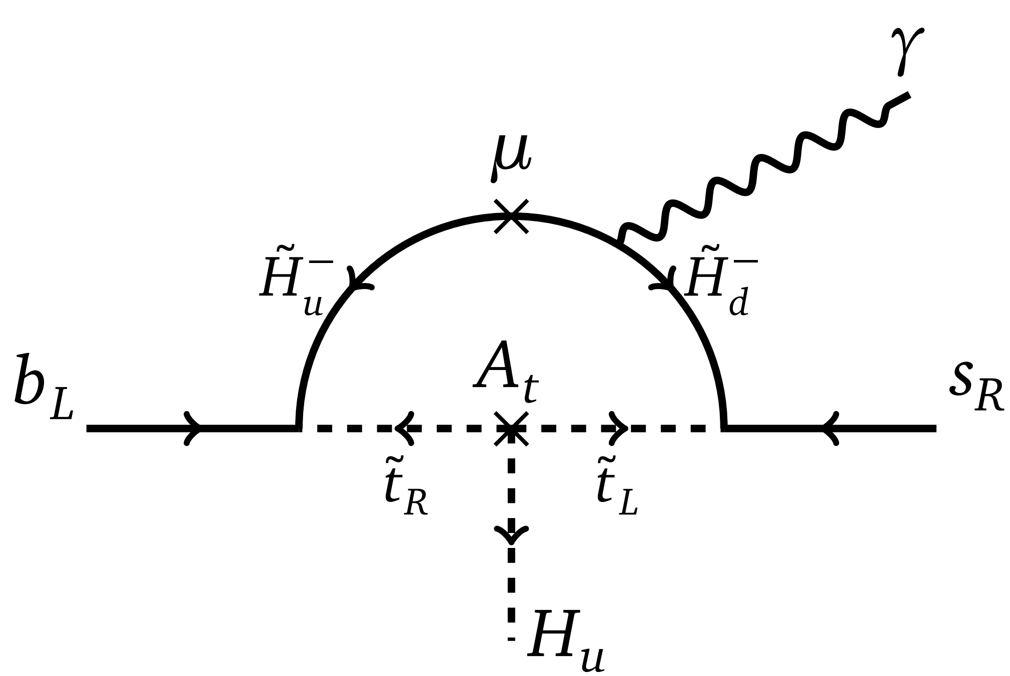
If time allows:

Natural SUSY and b→sγ

A. Katz, M. Reece, A. Sajjad 1406.1172

Stops and higgsinos, key to naturalness, give a loop correction to b→sγ.

$$\mathscr{M}_{\tilde{t};\tilde{h}}(b \to s\gamma) \sim m_t^2 \frac{A_t \mu}{m_{\tilde{t}}^4} \tan\beta$$



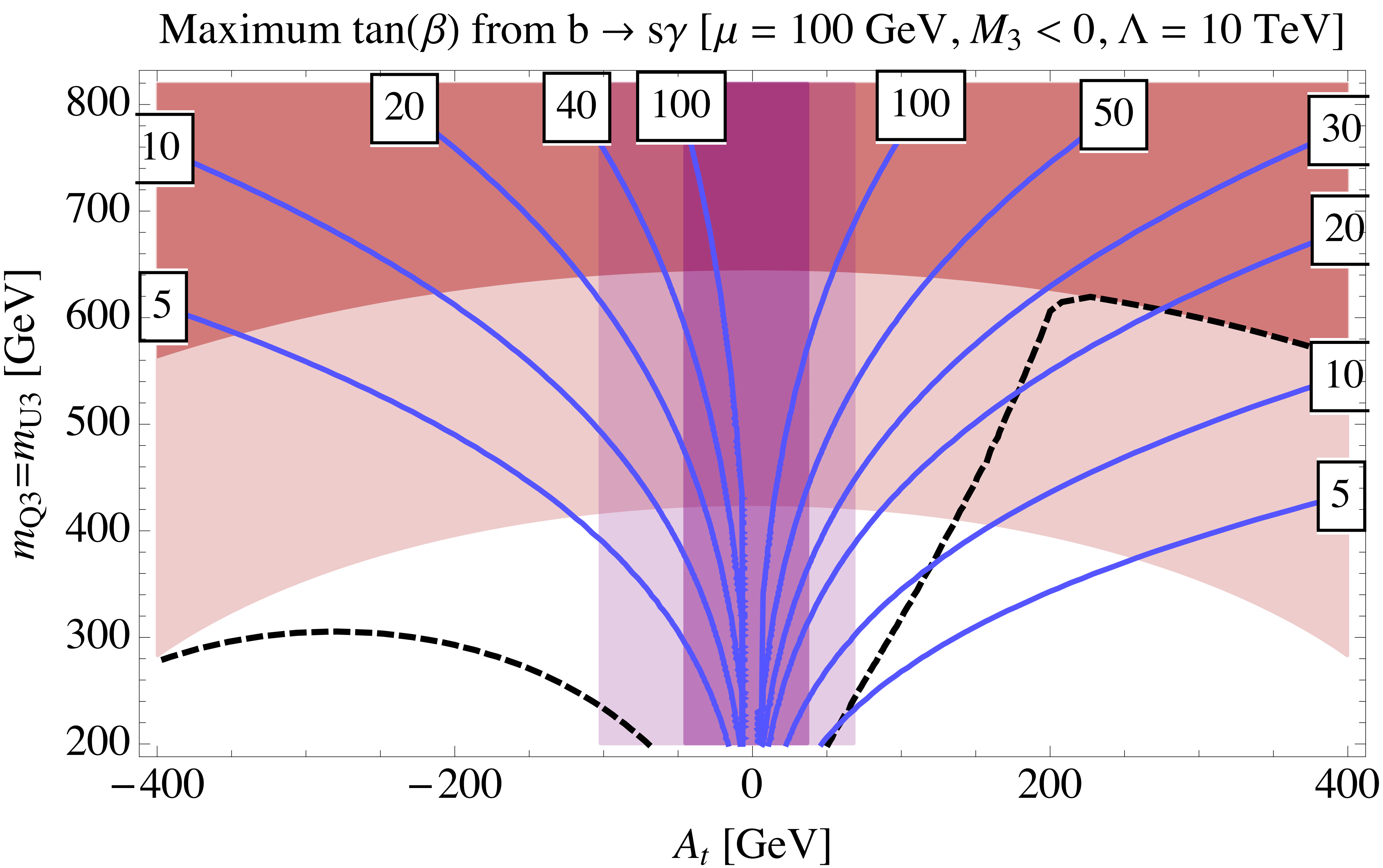
Higgsino mass μ can't be too small (LEP direct constraint)

A_t can't be too small (RG prop. to gluino mass)

Stop mass not too big (naturalness)

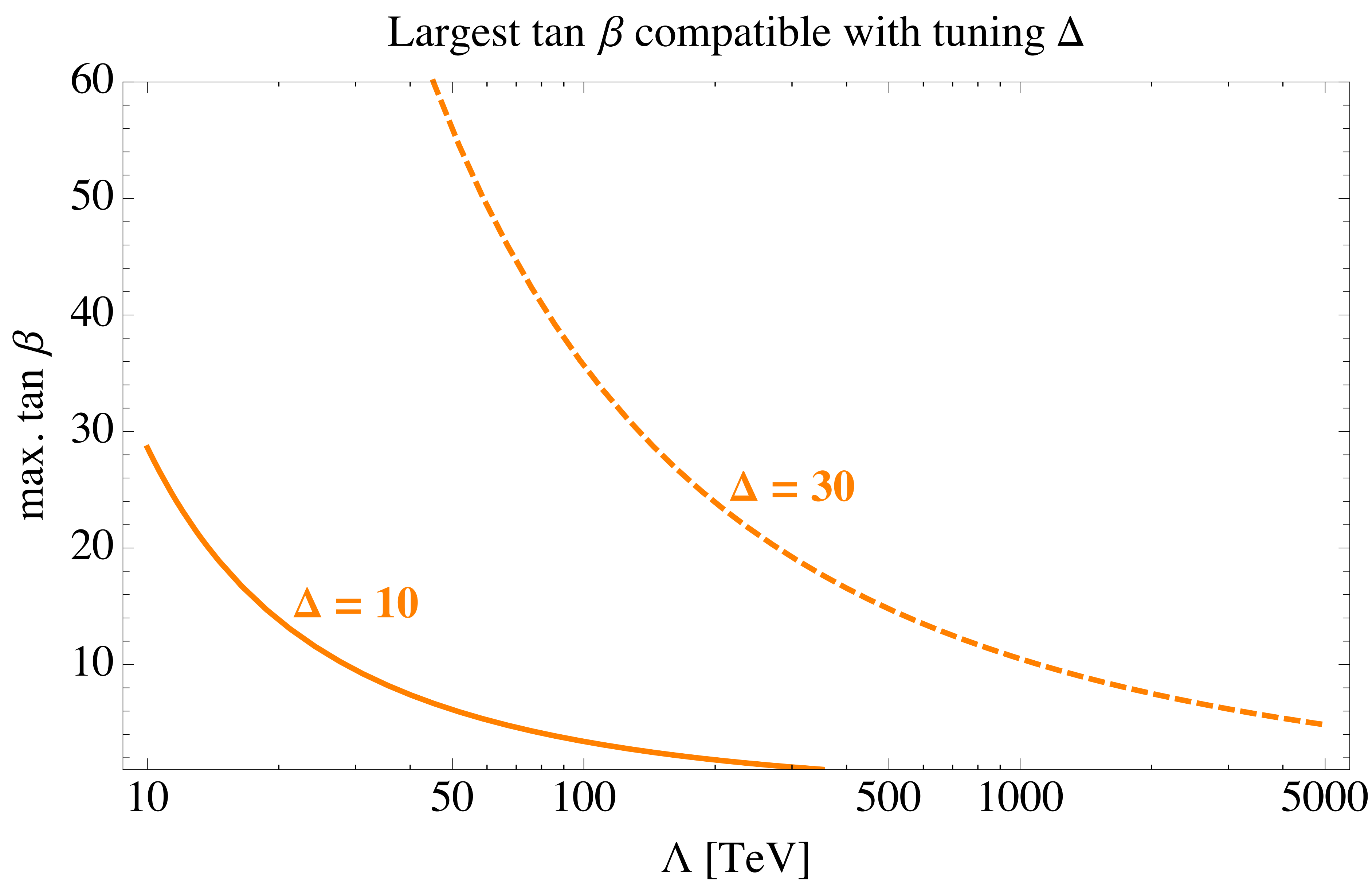
So: coefficient not too small!

Natural SUSY and b→sγ



In natural theories, it's hard to get tan beta to be large.

Bounding tan beta with $b \to s\gamma$

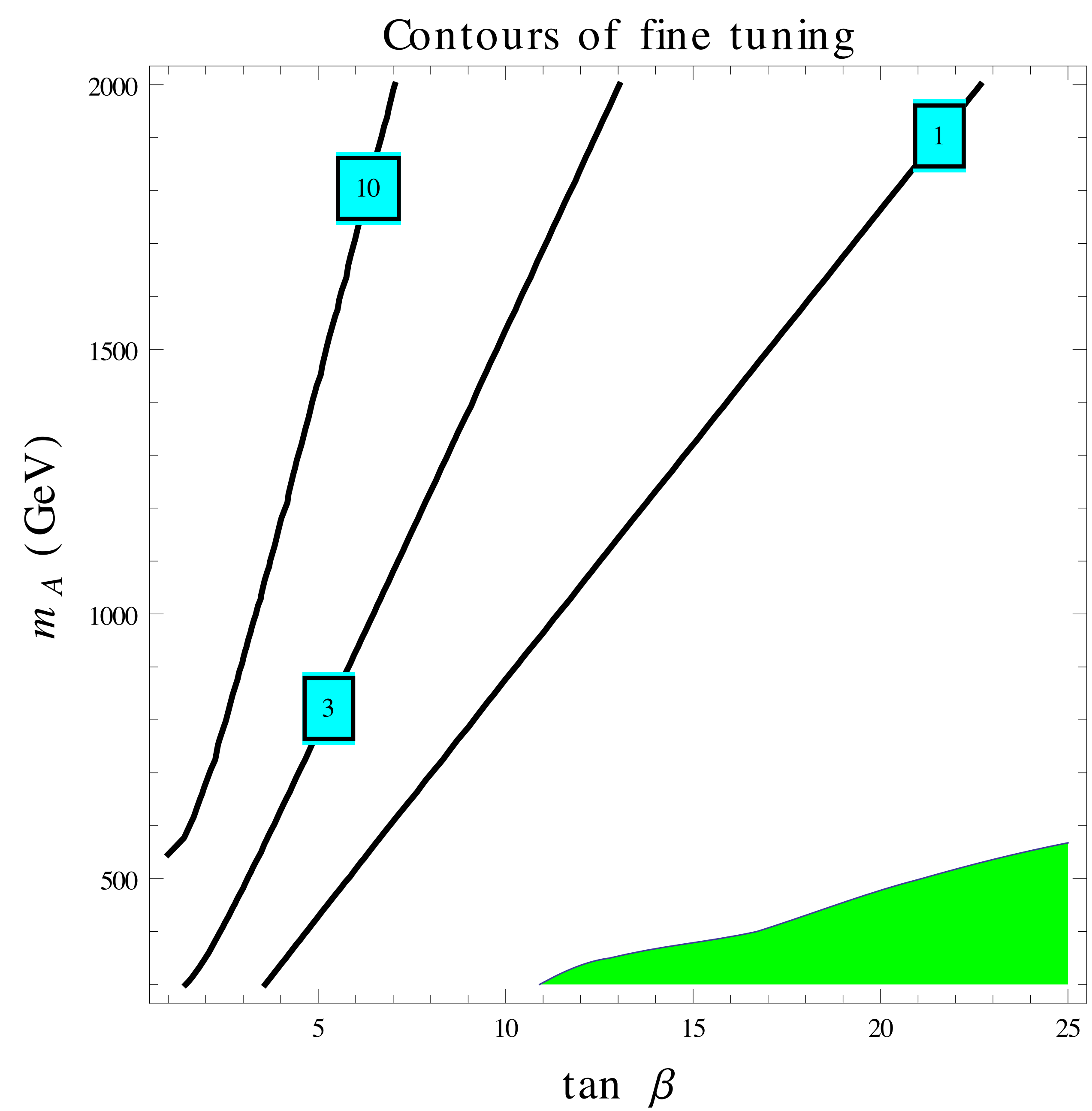


In natural theories, it's hard to get tan beta to be large.

SUSY Heavy Higgs Bosons

$$\left|\frac{\partial \log v^2}{\partial \log M_d^2}\right| \longrightarrow_{\tan\beta\to\infty} \frac{2m_A^2 + 2m_h^2 + 3m_Z^2}{m_h^2 \tan^2\beta}.$$

Barring fine-tuning or very low-scale mediation of SUSY breaking, the bound from b→sγ leads us to expect heavy Higgs bosons (*H*⁰, *A*⁰, *H*⁺ᐟ⁻) near the TeV scale. Could be out of LHC reach, but **a large chunk of the natural parameter space is in reach!**



More about *R*-parity violation

RPV has received a lot of attention recently in the context of natural SUSY (hiding superpartners from the LHC).

I think we should also be thinking about RPV *in the unnatural, mini-split SUSY context*. Removes the wino DM problem. Produce **winos**, which **decay**. How do they decay?

$W_{RPV} = u^c d^c d^c$ has gotten a lot of recent attention (e.g. MFV RPV). Good for hiding from LHC searches (multi-jet signals).

I want to comment on an option that received less recent attention: bilinear RPV, with 2-body wino decays at the LHC.

(for older work: see hep-ph/9612447 by Mukhopadyaya and Roy; hep-ph/0410242 by Chun and Park; also, for 3-body decays in bilinear RPV, Graham, Kaplan, Rajendran, Saraswat, 1204.6038)

Bilinear RPV

If we violate *R*-parity by violating lepton number, can add

$$W_{LNV} = \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \epsilon_i \mu L_i H_u$$

the bilinear term can be rotated away, but in general still have bilinear soft terms remaining:

$$\mathcal{L}_{LNV} \supset -\left(B_{L_i\mu}\mu \tilde{L}_i H_u + \tilde{m}^2_{H_d,L_i}\tilde{L}_i H_d^\dagger + \mathrm{h.c.}\right)$$

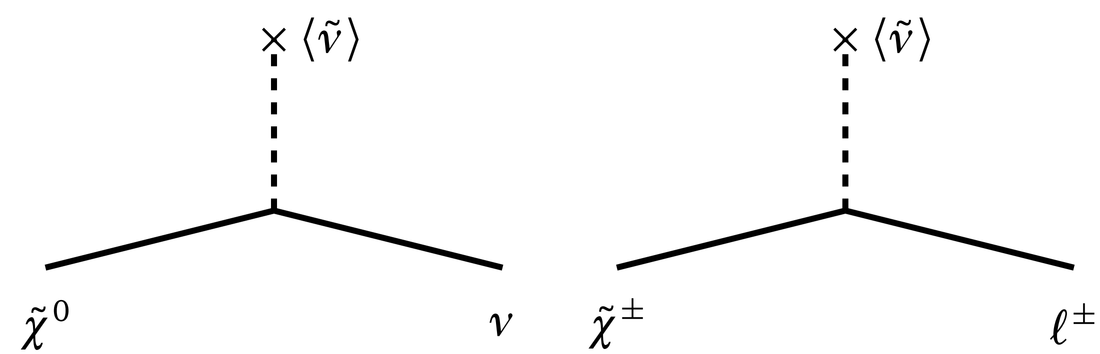
In the mini-split context would guess $B_{L_i\mu}\mu,\ \tilde{m}^2_{H_d,L_i} \sim \epsilon m^2_{3/2}$

Once the Higgs gets a VEV, these terms become sneutrino tadpoles, so the sneutrino gets a VEV:

$$\langle \tilde{\nu} \rangle \sim \epsilon v$$

Sneutrino VEVs

The sneutrino VEV has several interesting consequences. Gauginos mix with leptons:



If winos are the LSPs, this will give them new decay modes:

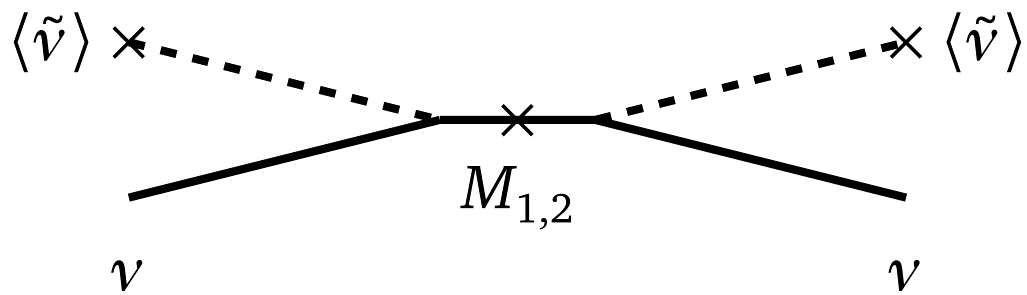
$$\tilde{W}^0 \to Z\nu, W^\pm \ell^\mp$$

$$\tilde{W}^\pm \to Z\ell^\pm, W^\pm \nu$$

This would be a worthwhile search channel at the LHC.
(Probably the lepton is mostly tau? Need flavor model.)

Bilinear RPV

Also get a contribution to neutrino masses:



$$m_\nu \sim \epsilon^2 \frac{v^2}{M_{1,2}}$$

This implies an upper bound $\epsilon \sim 10^{-6}$.

This gives a *lower* bound on the lifetime of the two-body wino decays, ~ 100 microns.* So should look for

$$\tilde{W}^0 \to Z\nu, W^\pm \ell^\mp$$
$$\tilde{W}^\pm \to Z\ell^\pm, W^\pm \nu$$

with displaced vertices! (Possibly macroscopically displaced; **standard lepton ID may fail**.)

* Disclaimer: I haven't plugged in all order-one factors; hope to study this more carefully soon.