Natural SUSY's Last Hiding Places

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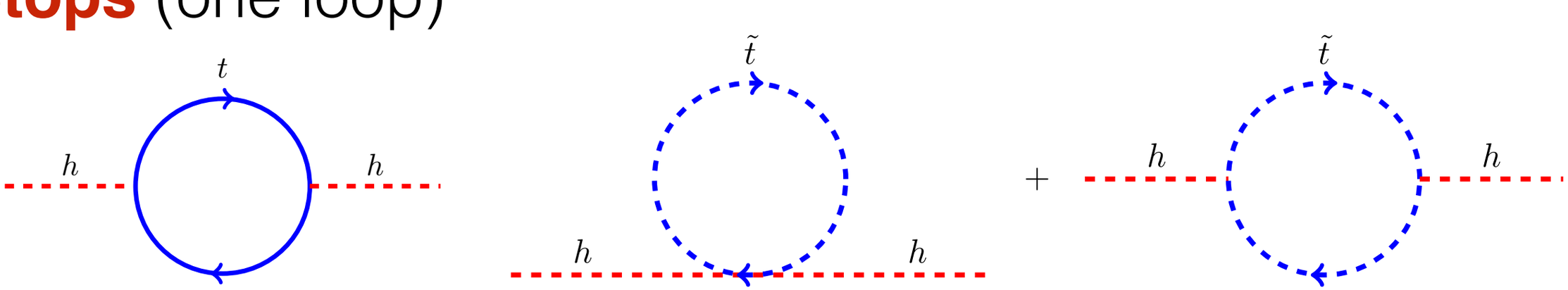
Harvard University
at Naturalness 2014, Nov. 16, 2014

Natural SUSY

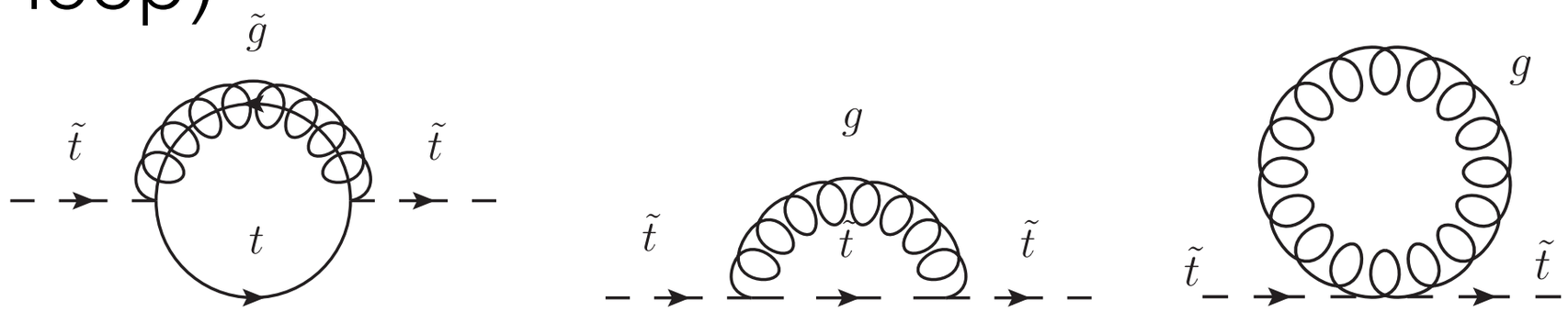
Reviewed in earlier talks at this workshop:

- **Higgsinos** (tree level); also, to some extent, heavy Higgses (2HDM), esp. if tan beta not large

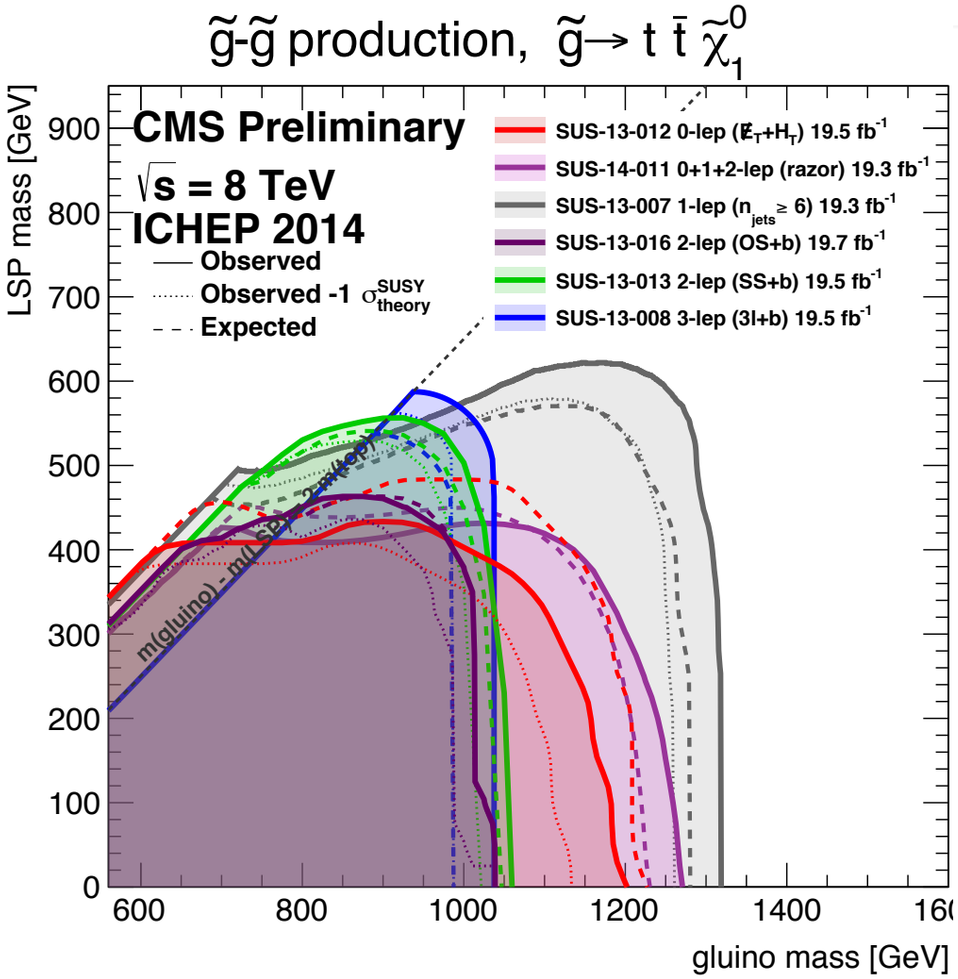
- **Stops** (one loop)

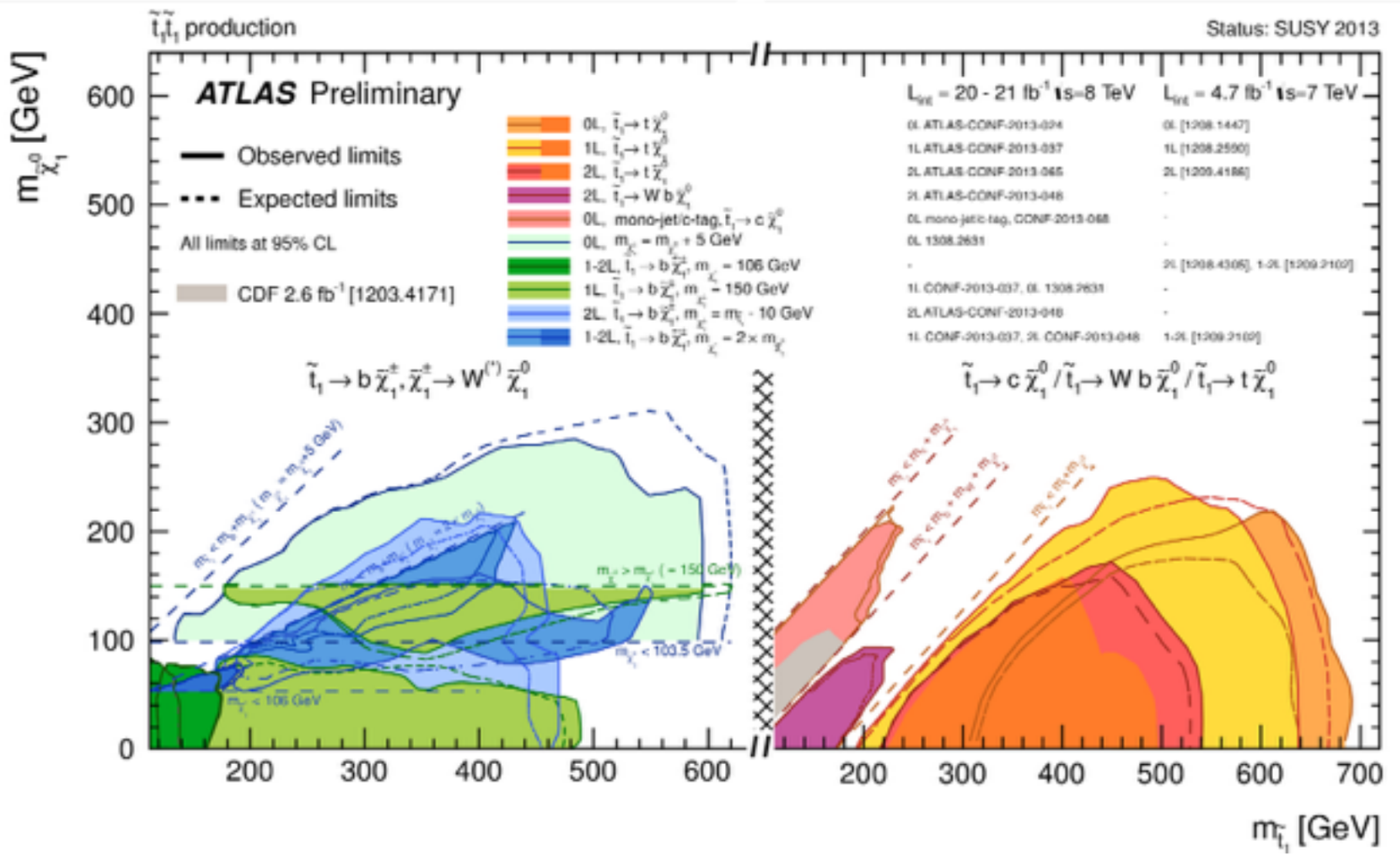


- **Gluinos** (two loop)



“Standard” Gluinos and Stops





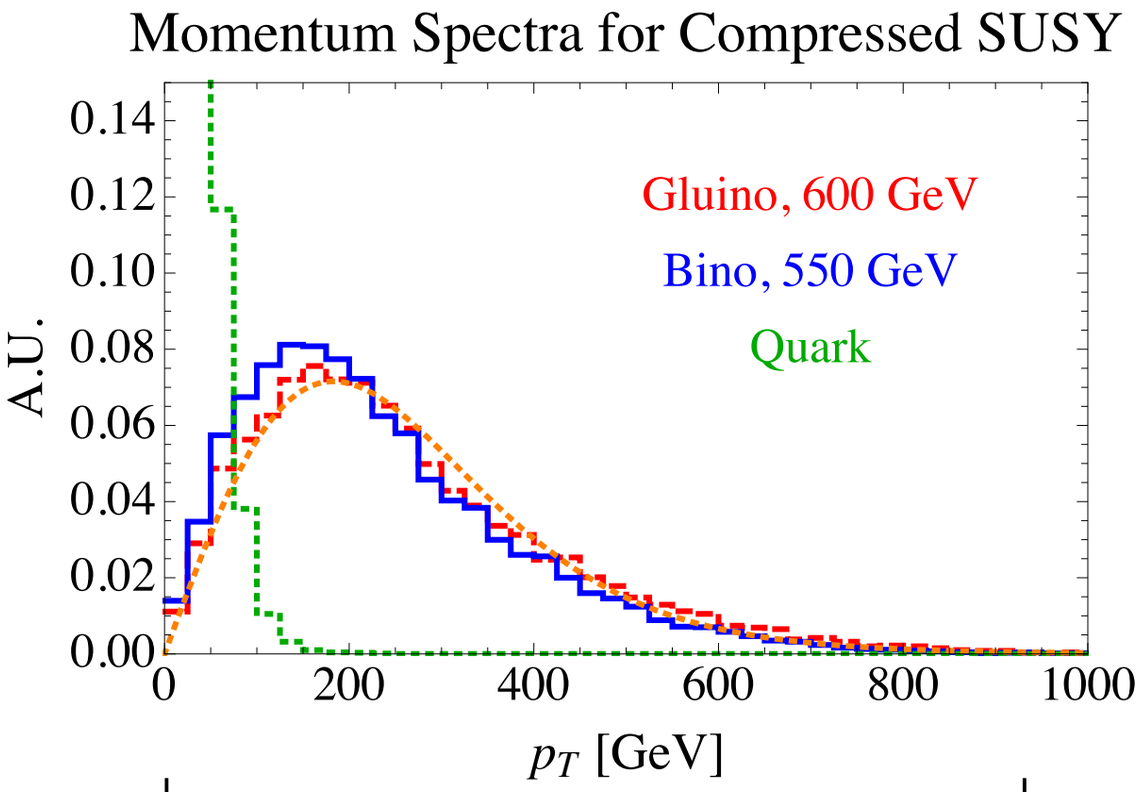
Searches with missing momentum are pushing at the 10% tuning boundaries in stop and gluino masses.

How Can Superpartners Hide?

Several possibilities for **evading MET searches**:

- Decay entirely to visible particles (RPV).
- Decay to invisible particles, but with longer cascades, more visible particles, MET diluted (e.g. Hidden Valley)
- Decay to invisible particles, with more *invisible* particles so the visible energy is diluted ("Hiding MET with MET")
- Degeneracies in the spectrum: smaller phase space means smaller momentum for decay products
  - First version: visible particles are softer ("Compressed SUSY")
  - Second version: invisible particles are softer ("Stealth SUSY")

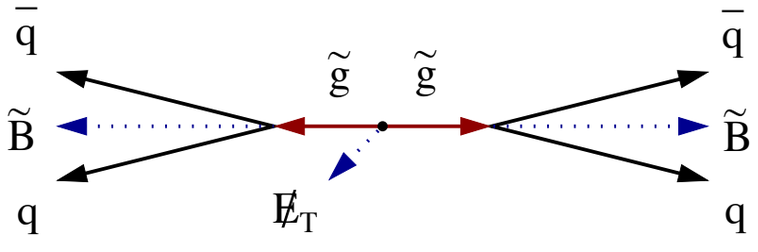
Small Phase Space



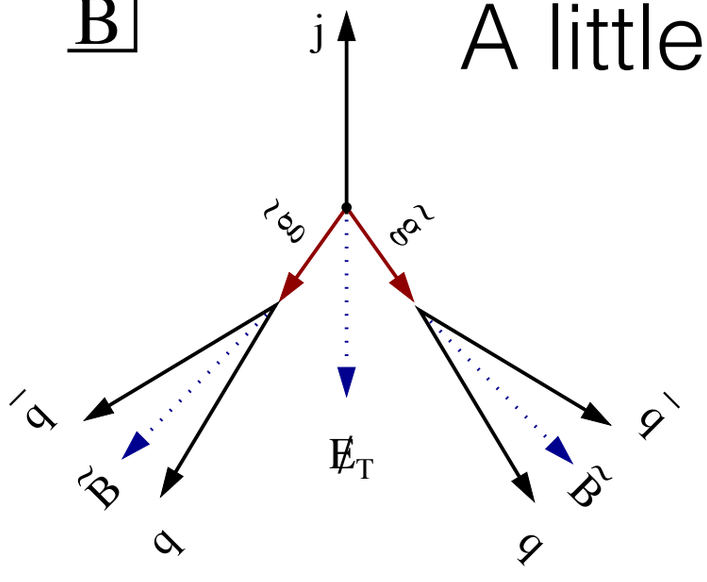
Heavy particle to one heavy and one light particle: heavy daughter inherits most of momentum in lab-frame. Light daughter is very soft.

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

A

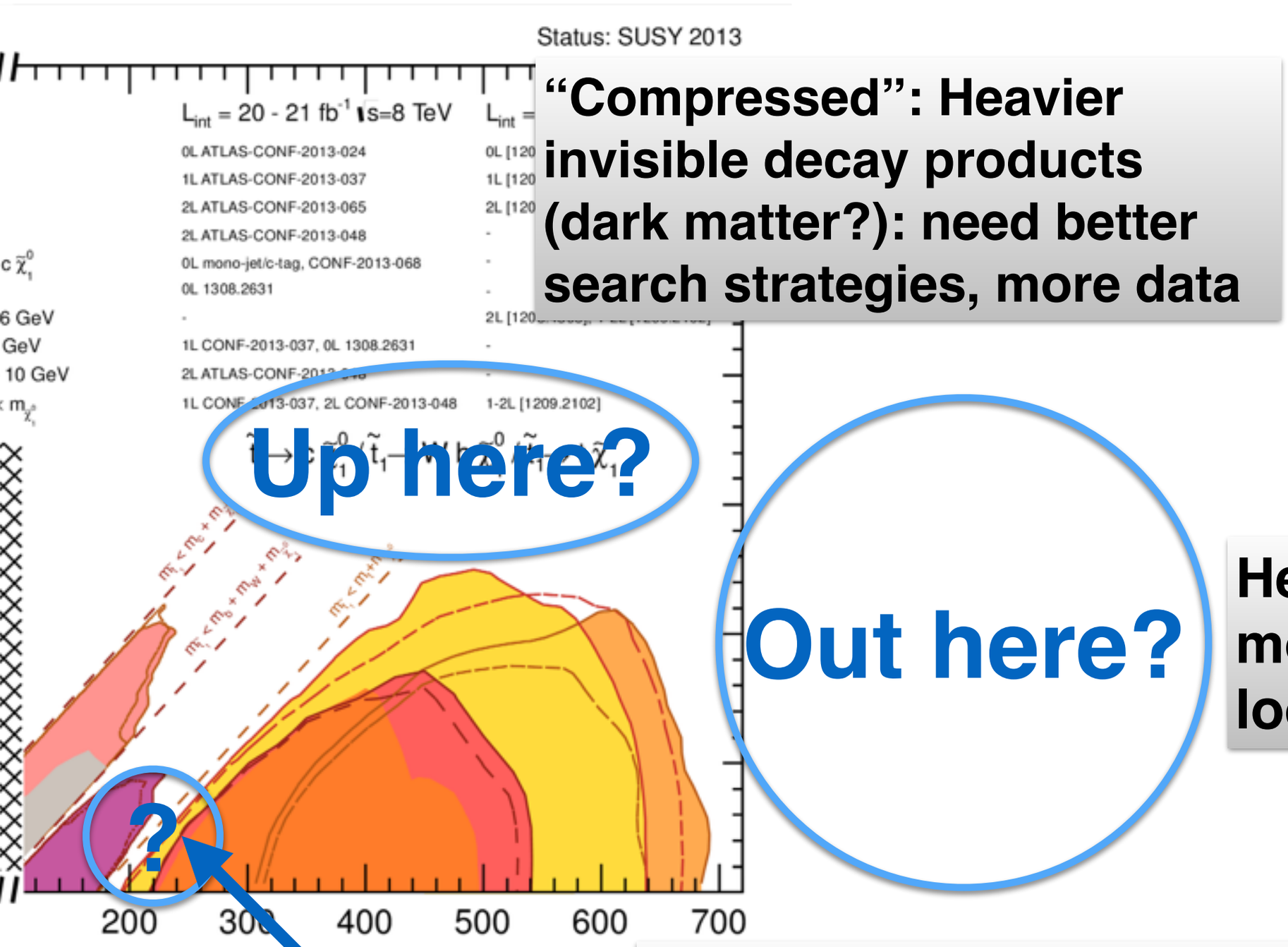


B



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

Stops: Improving the Reach



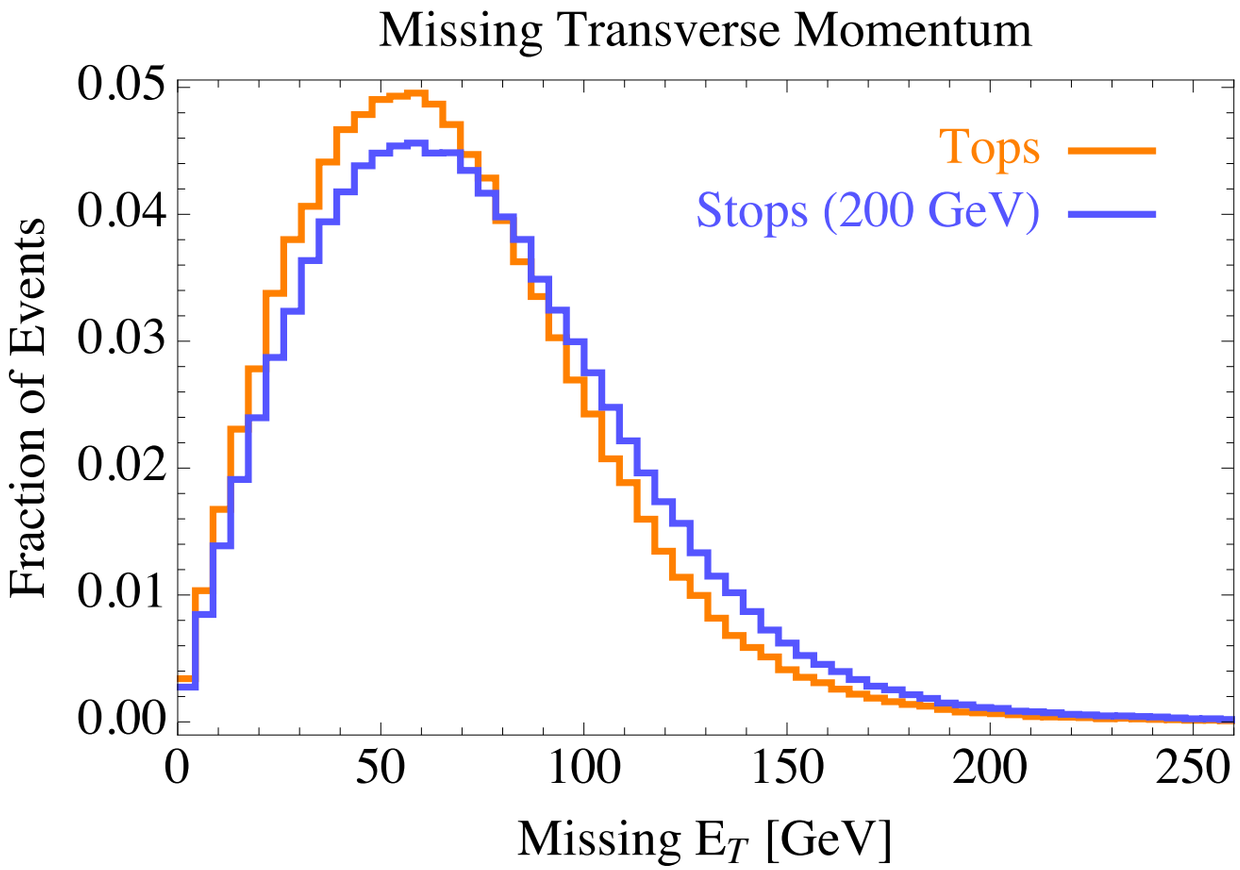
"Compressed": Heavier invisible decay products (dark matter?): need better search strategies, more data

Heavy stops: need more energy to look for them.

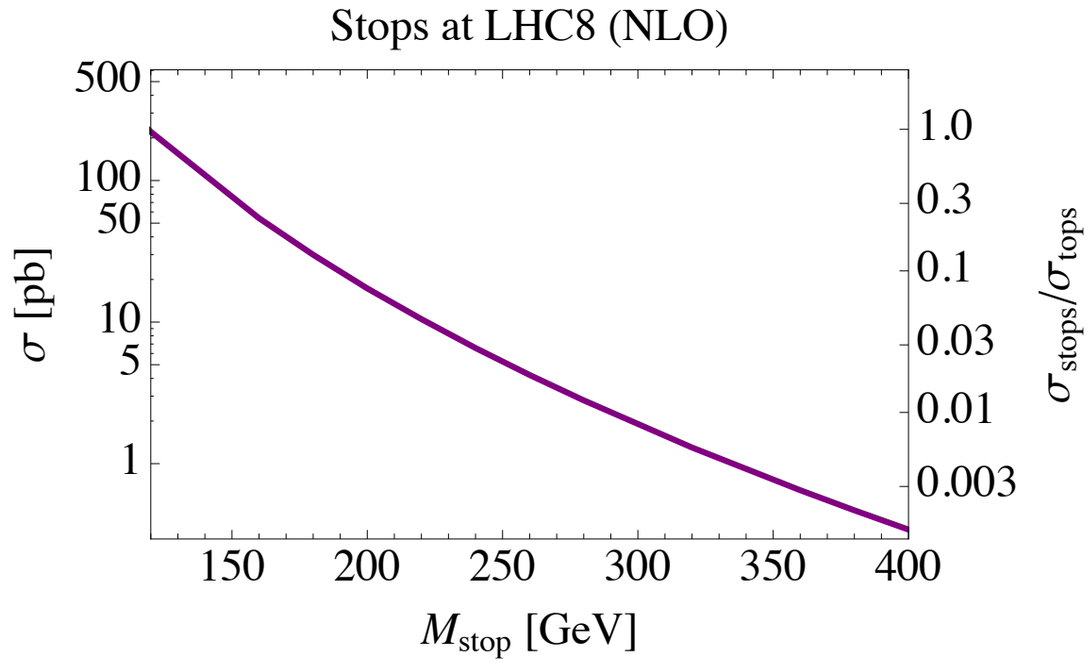
"Stealthy stops": J. Fan, MR, J. Ruderman. Need more precision.

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.



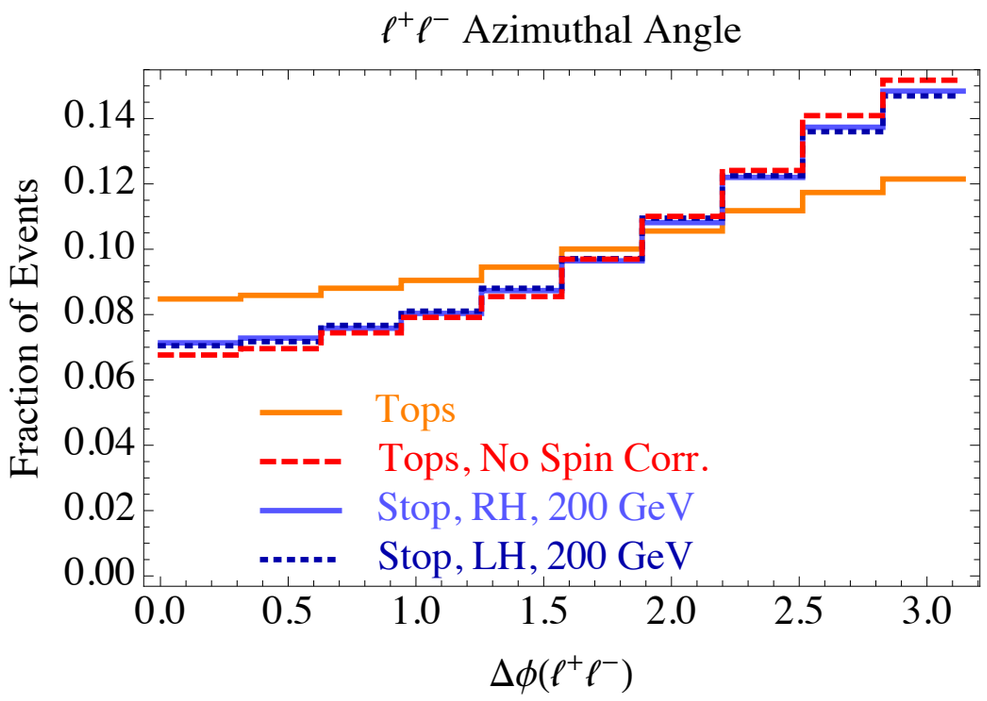
Z. Han, A. Katz, D. Krohn and MR, arXiv:1205.5808.



Small fraction of top cross section: hard to see!

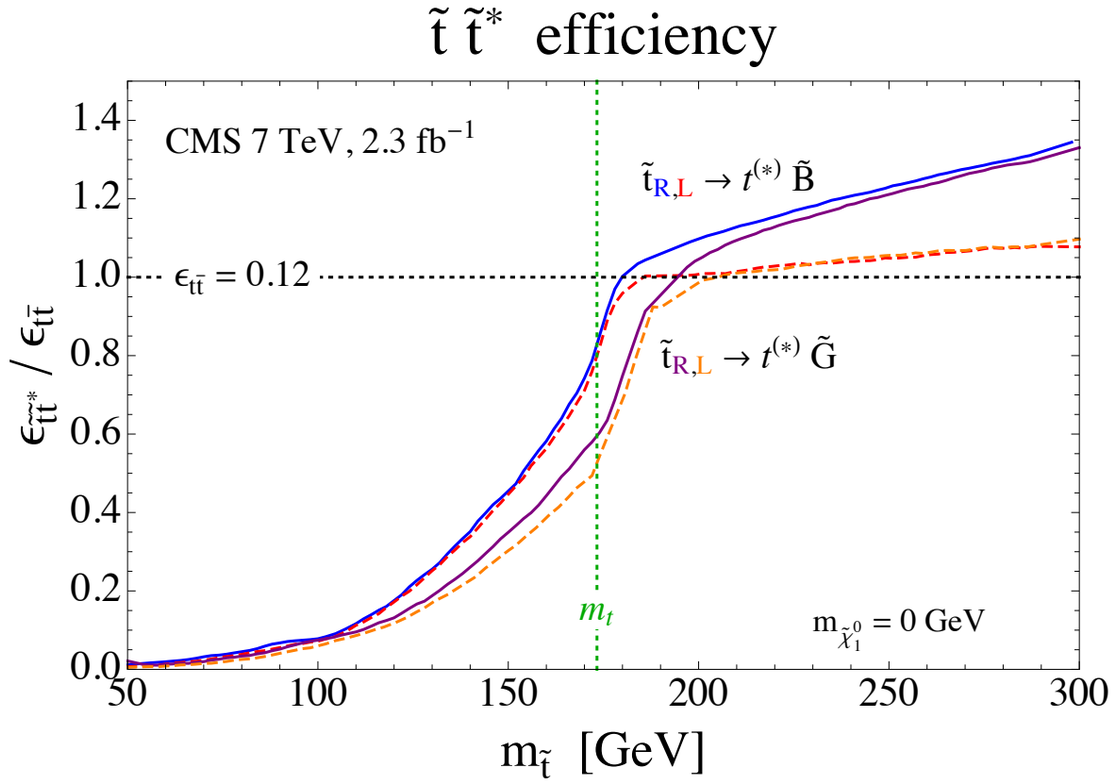
Precision Top Constraints

ATLAS has now followed up on these two theoretical proposals with recent experimental publications: you'll hear more about them in Frank Wuerthwein's talk!



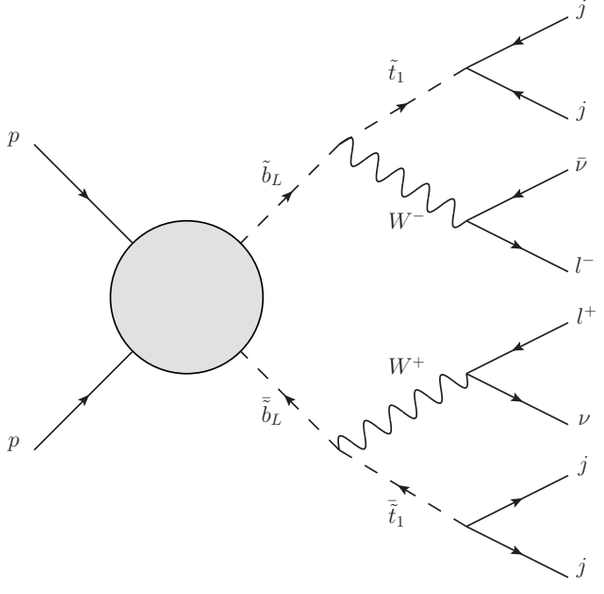
Spin correlations: proposed by Z. Han, A. Katz, D. Krohn, MR, arXiv:1205.5808

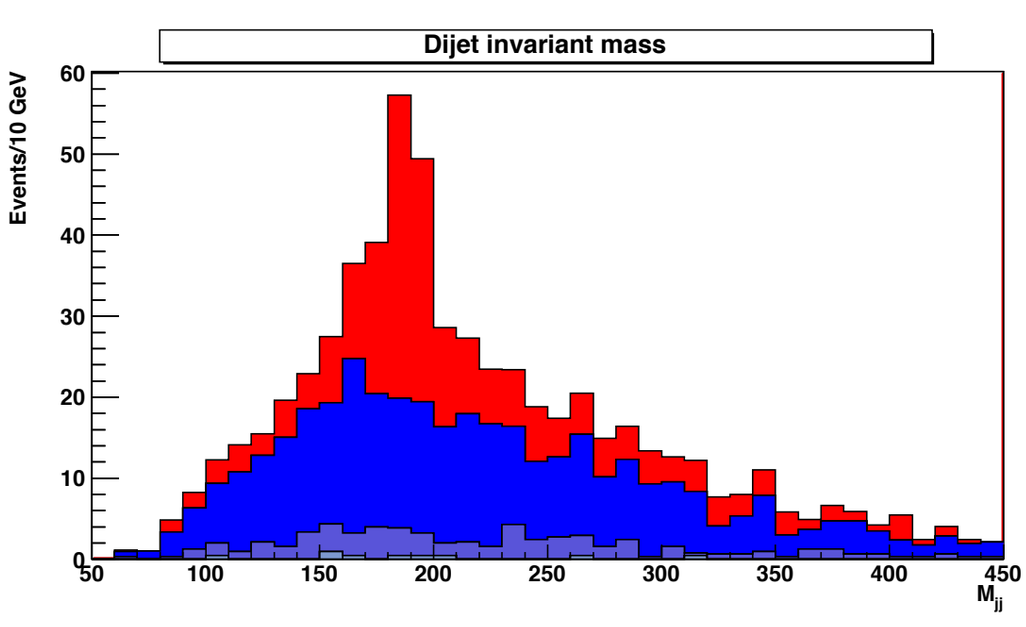
Cross section (NNLO theory): studied by Czakon, Mitov, Papucci, Ruderman, Weiler 1407.1043



Hiding with RPV

One way to hide SUSY is to make all the superpartners decay to things that could have been missed. Lots of recent attention on RPV stops, for example Brust, Katz, Sundrum 1206.2353:



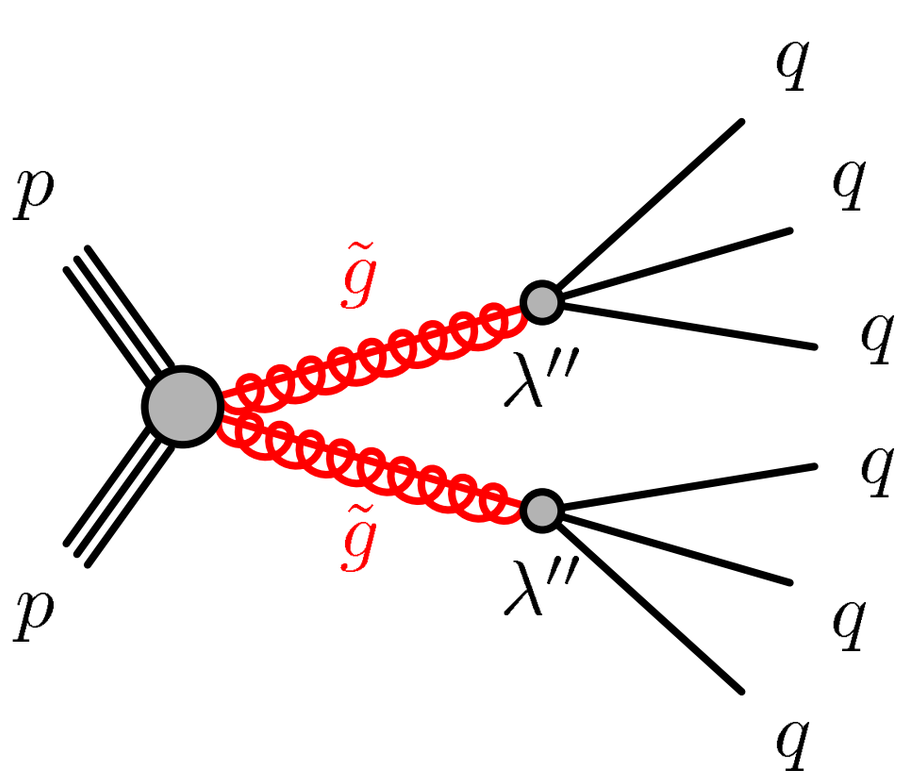


RPV is one of many ways to ***hide naturalness***. All energy goes to visible particles.

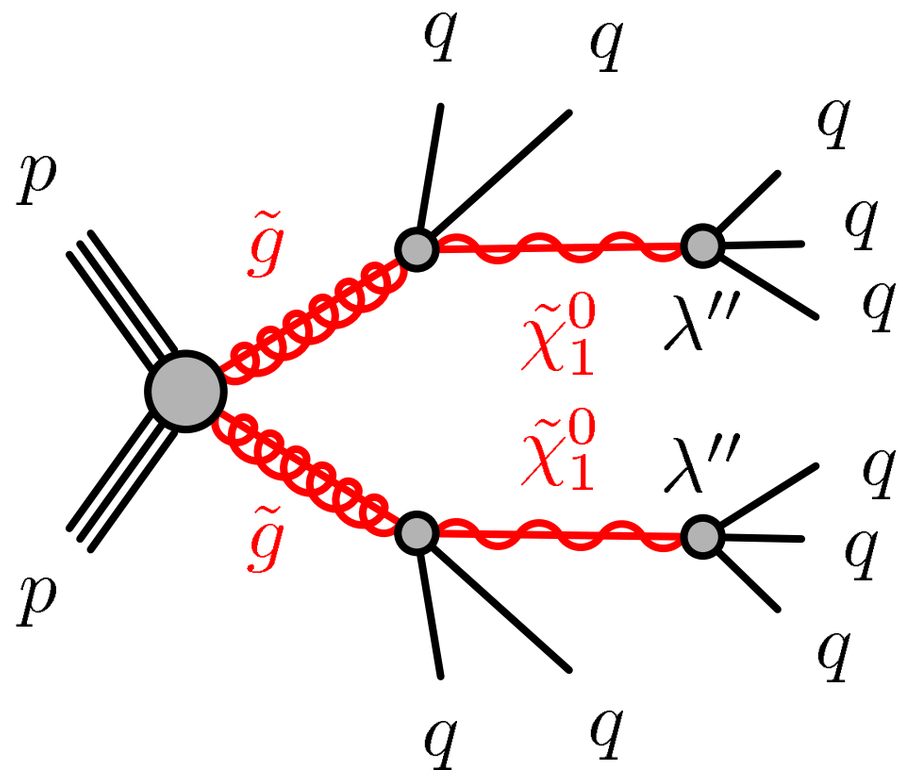
The *udd* superpotential operator can evade flavor constraints with MFV structure: Csáki, Grossman, Heidenreich 1111.1239

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.



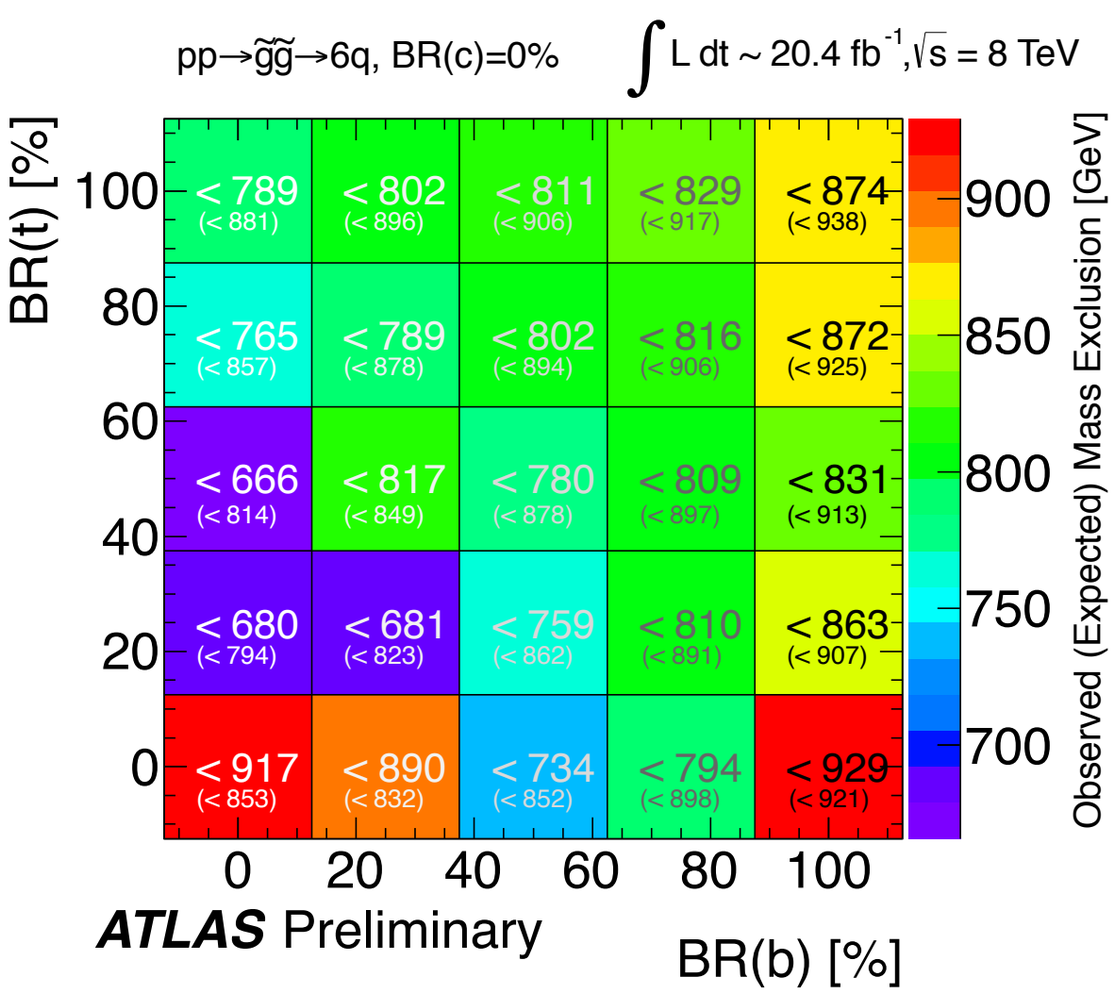
(a) 6-quark model

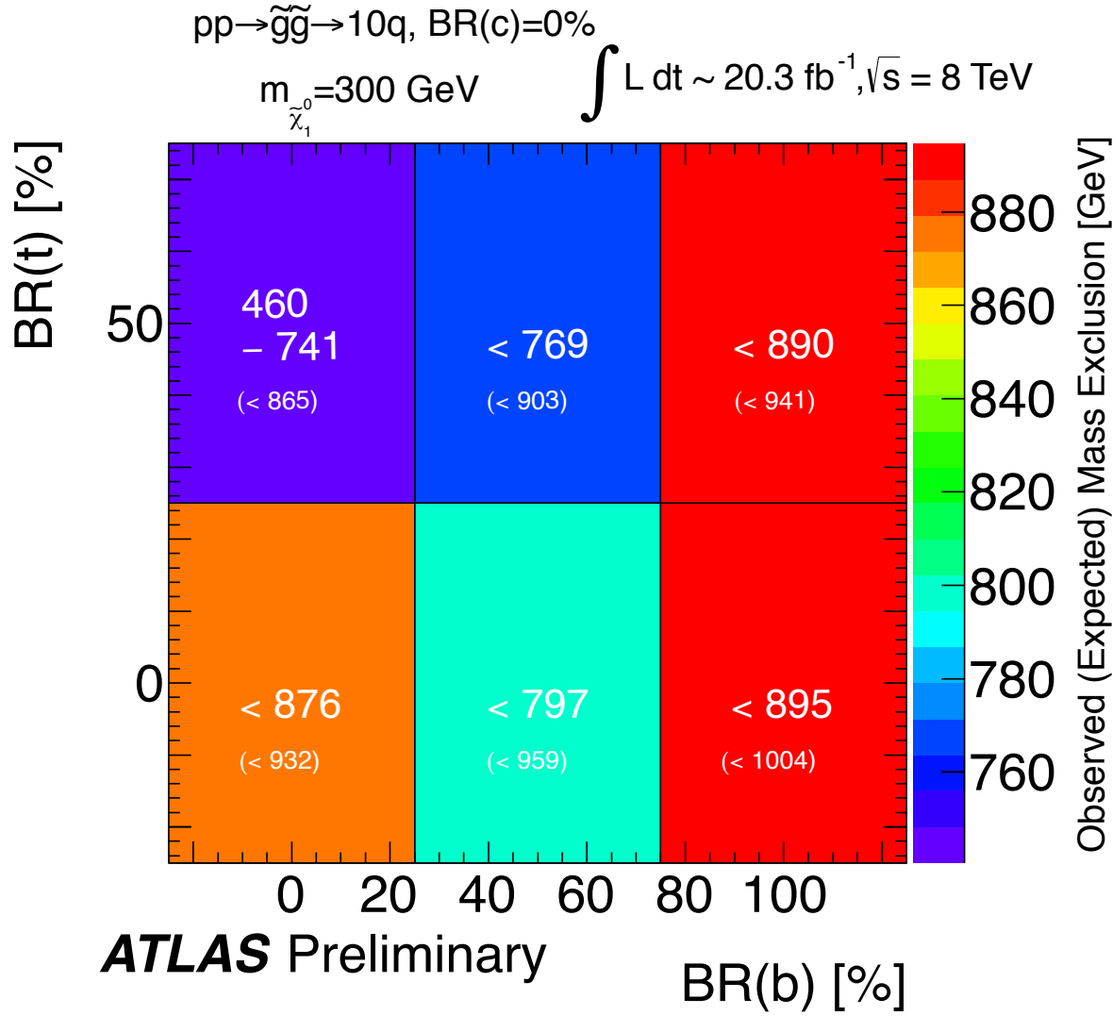


(b) 10-quark model

ATLAS-CONF-2013-091

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

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

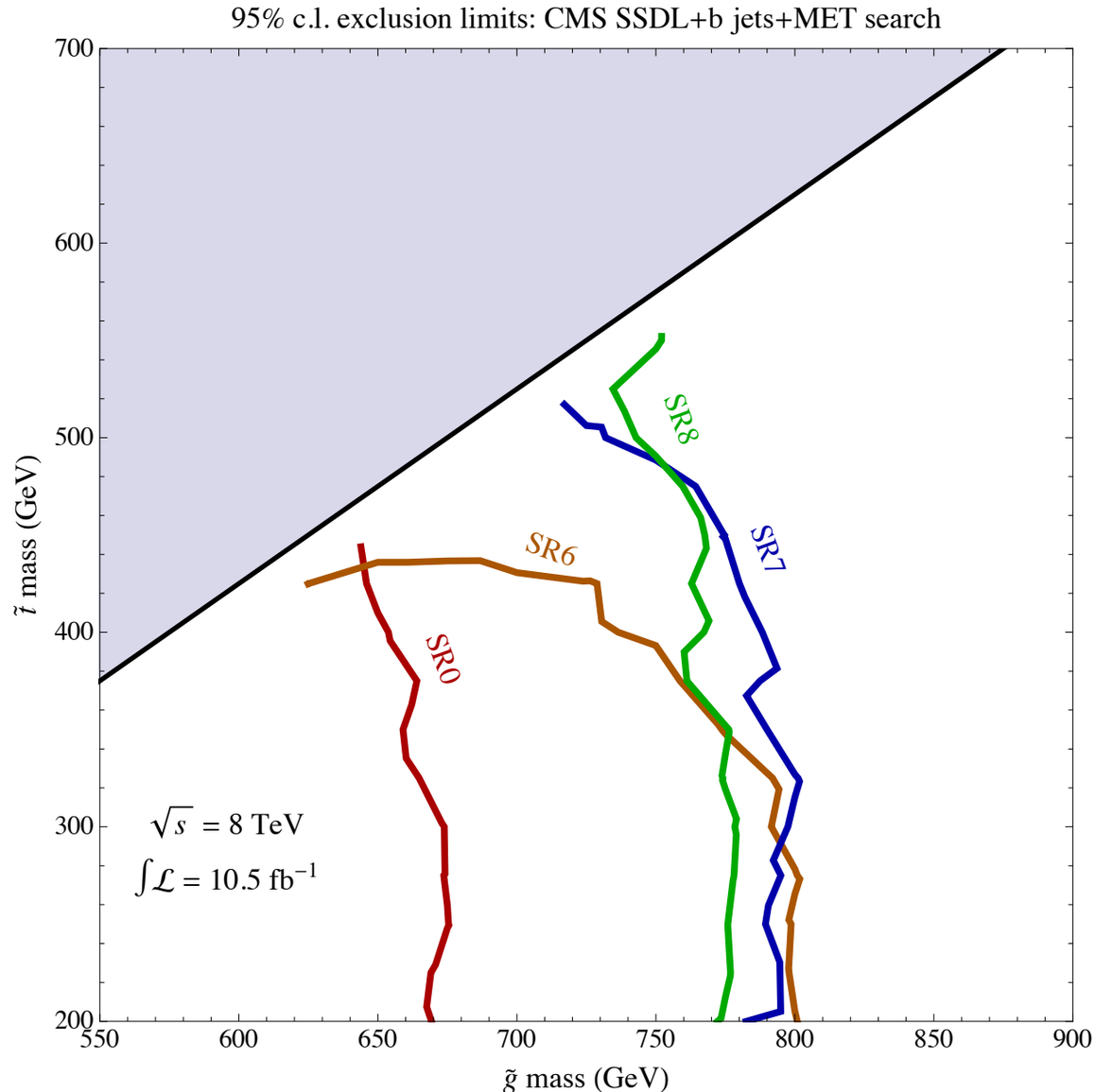
or

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

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!

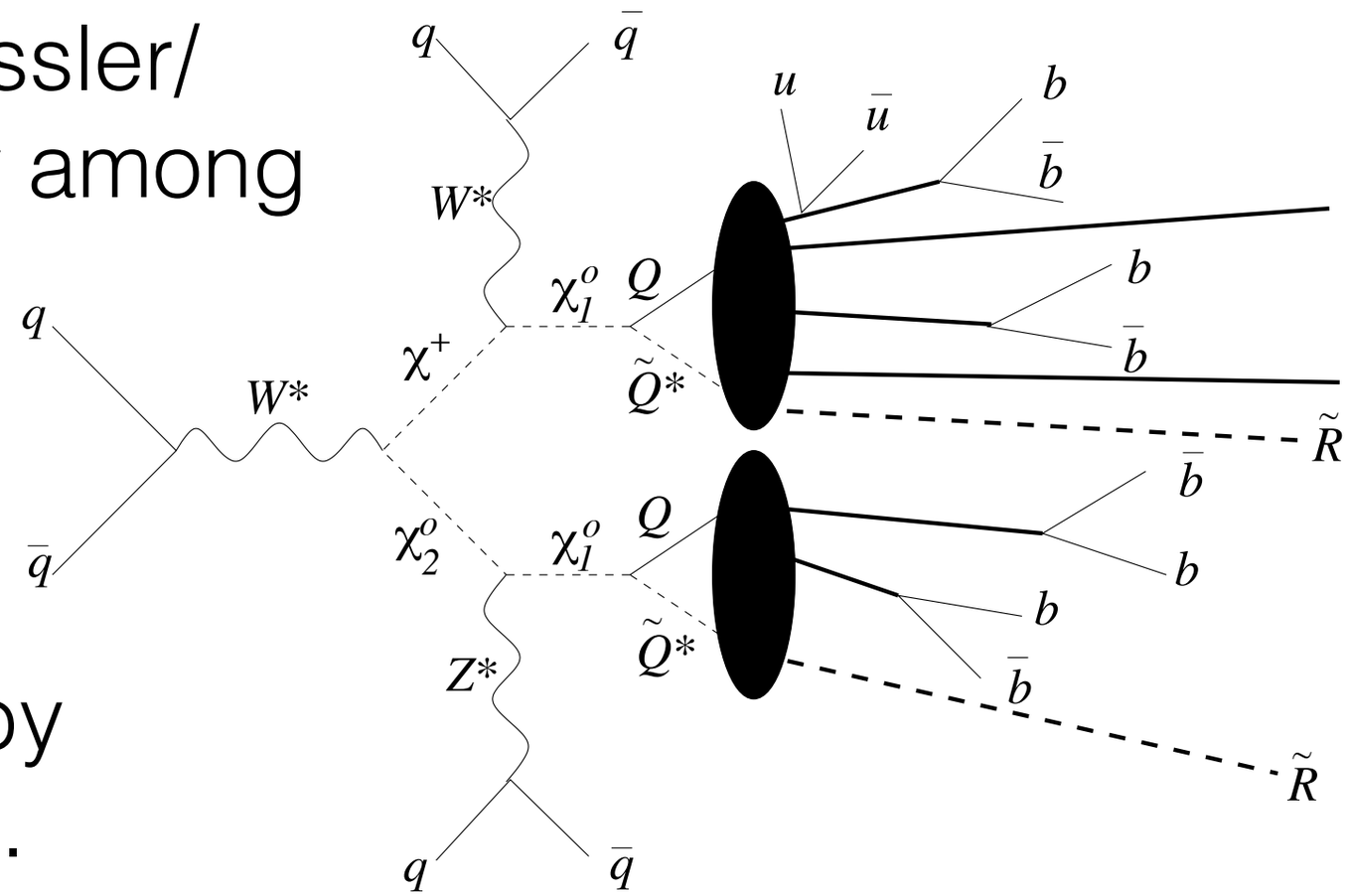


Hiding In Valleys

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

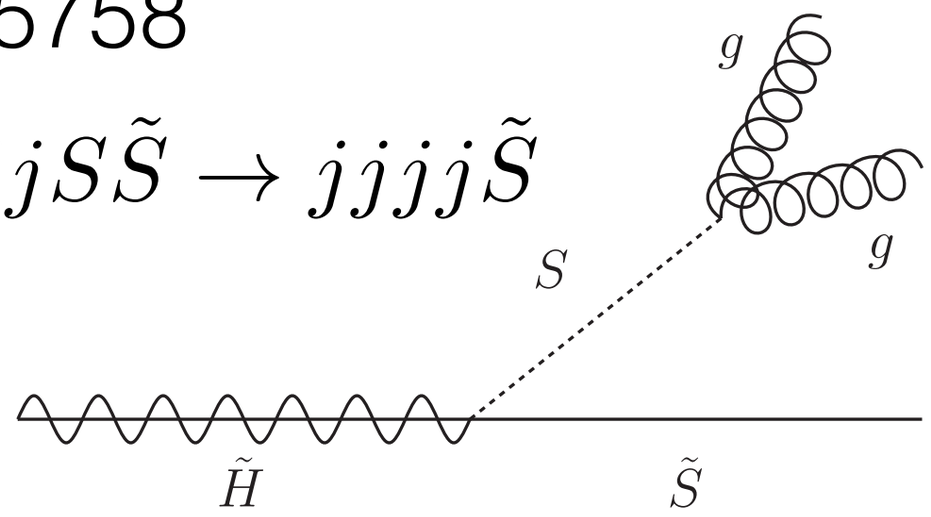


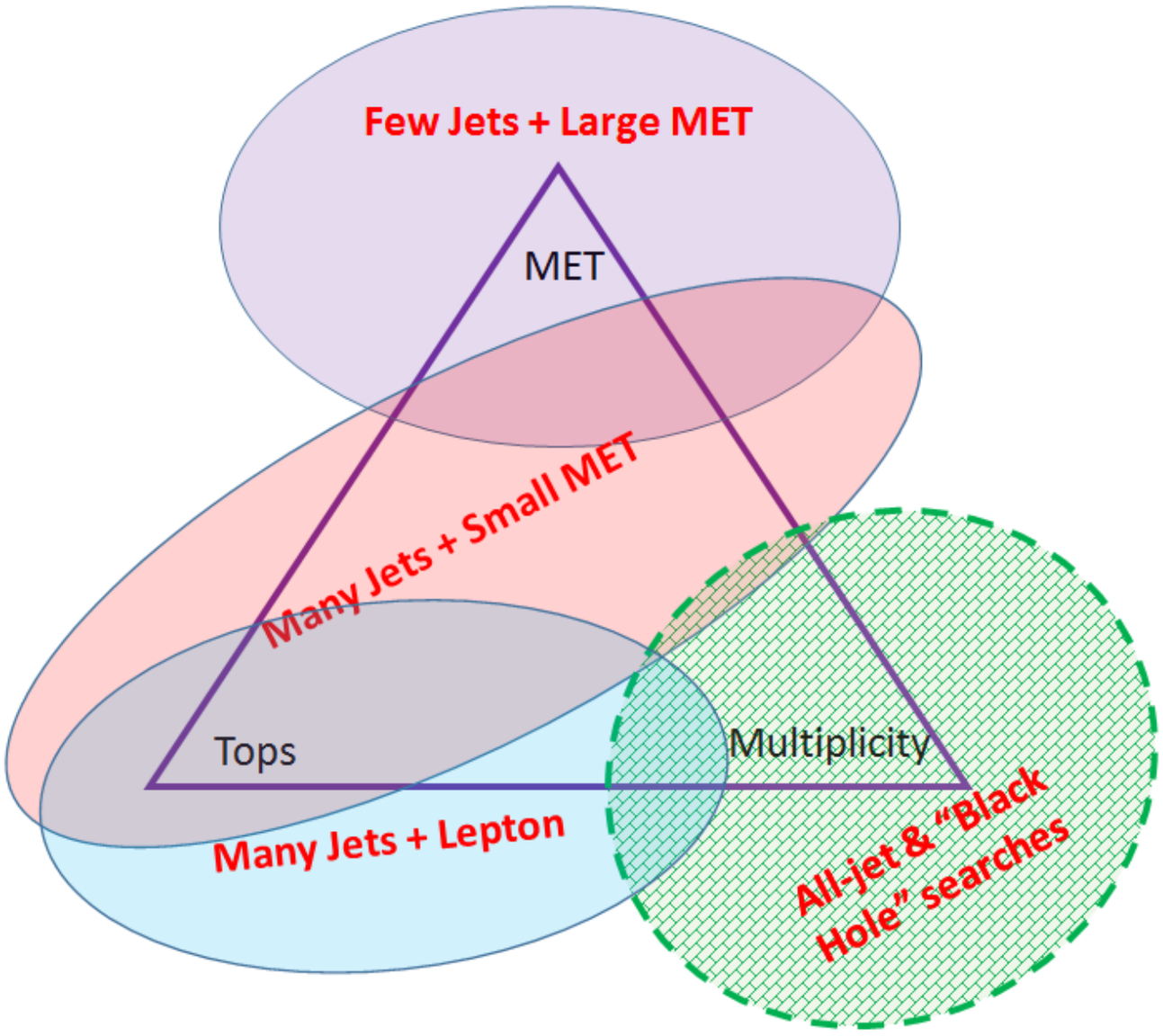
Roughly divide MET by #(final state particles).
See also lepton jets, etc.

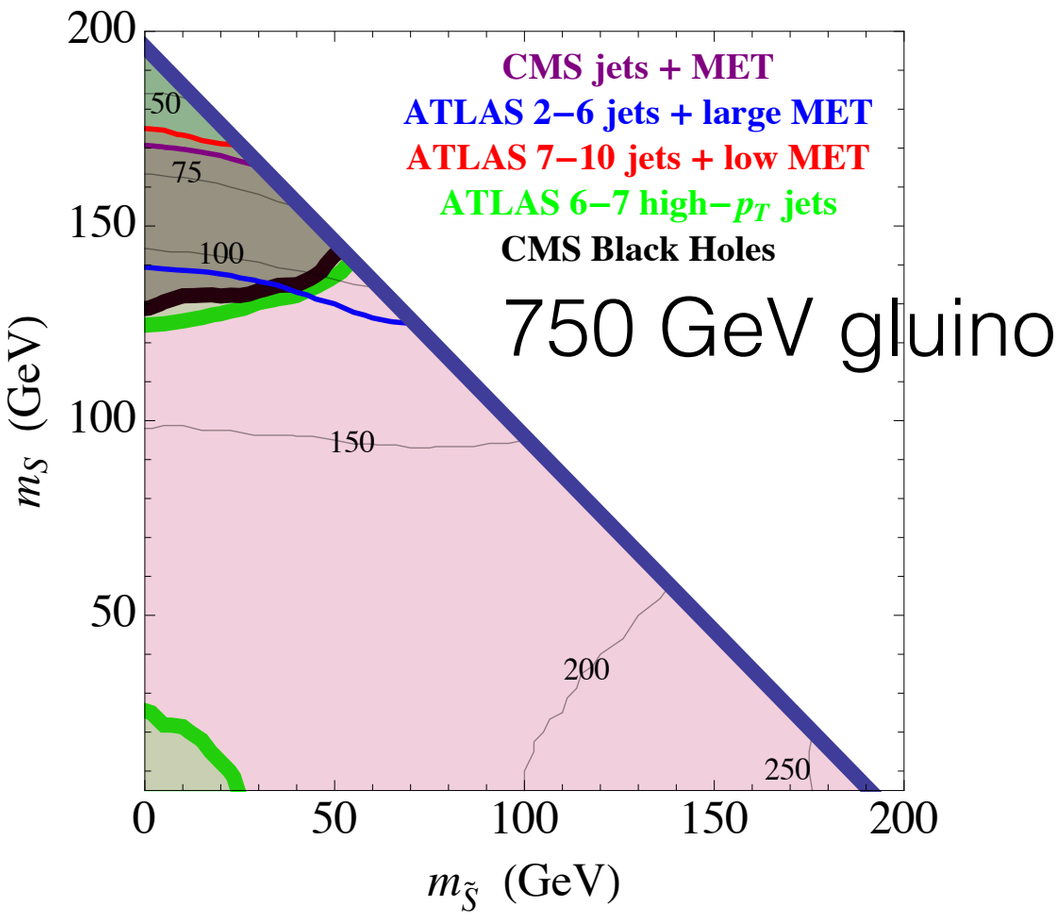
Hidden Valley Gluino Constraints

Evans, Kats, Shih, Strassler 1310.5758

$$\tilde{g} \to j\tilde{q} \to jj\tilde{H} \to jjS\tilde{S} \to jjjj\tilde{S}$$

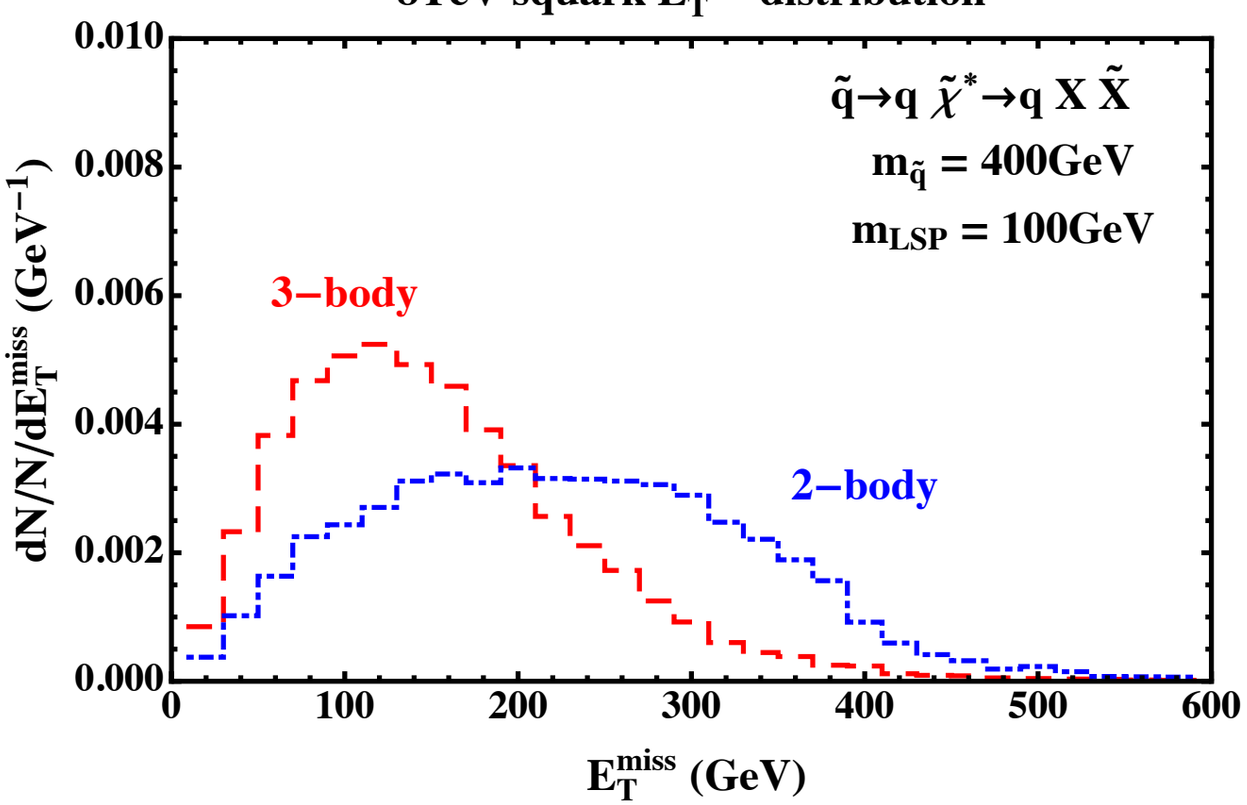






Hiding MET with MET

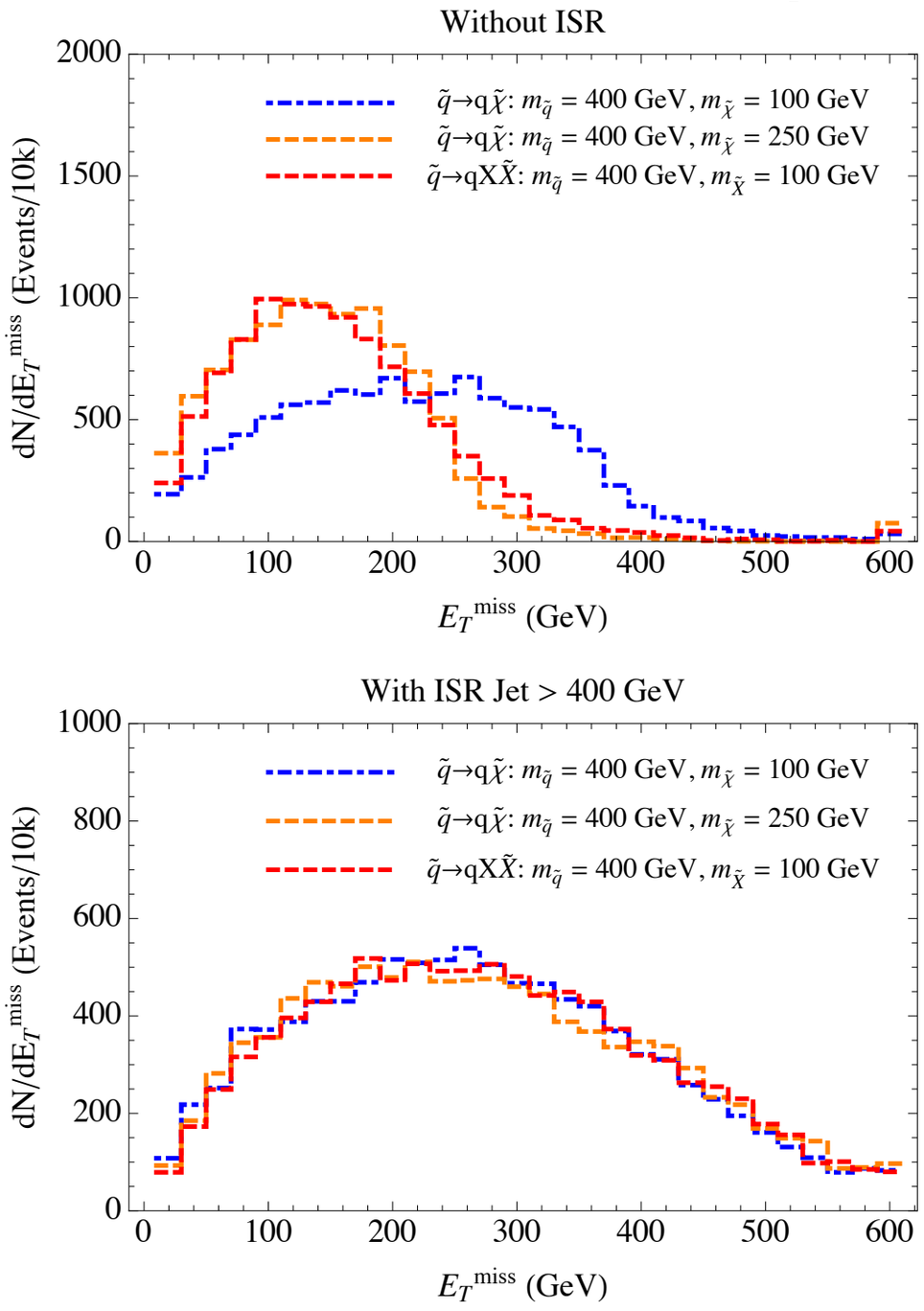
Decay chains with *more* invisible particles mean *less* visible energy. Need models w/ 3-body **"double-invisible"** decays.

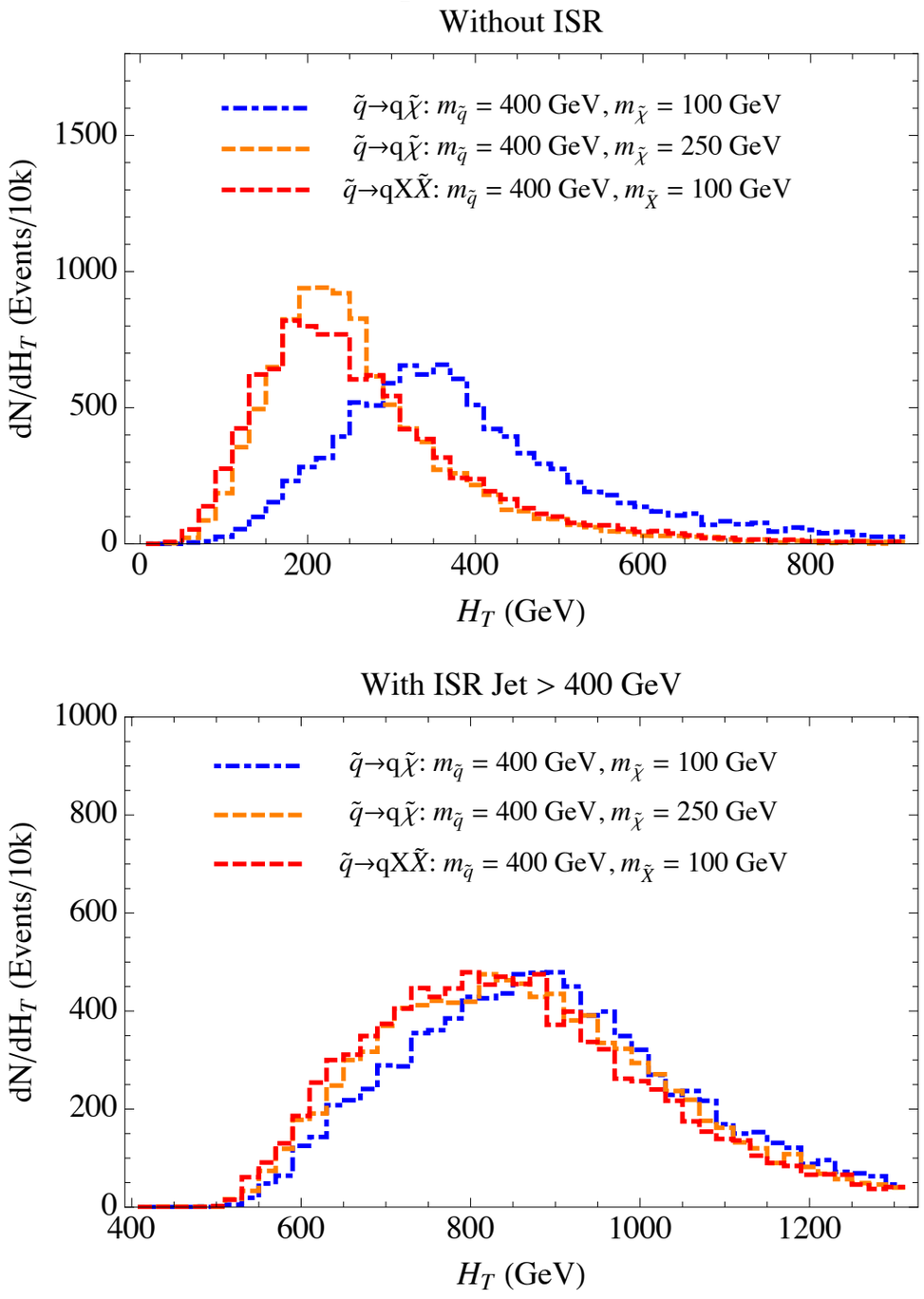


D. Alves, J. Liu, N. Weiner
1312.4965

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

Pheno of Hiding MET with MET = Compressed Spectrum





w/ Prateek Agrawal, unpublished.

ISR helps restore MET.

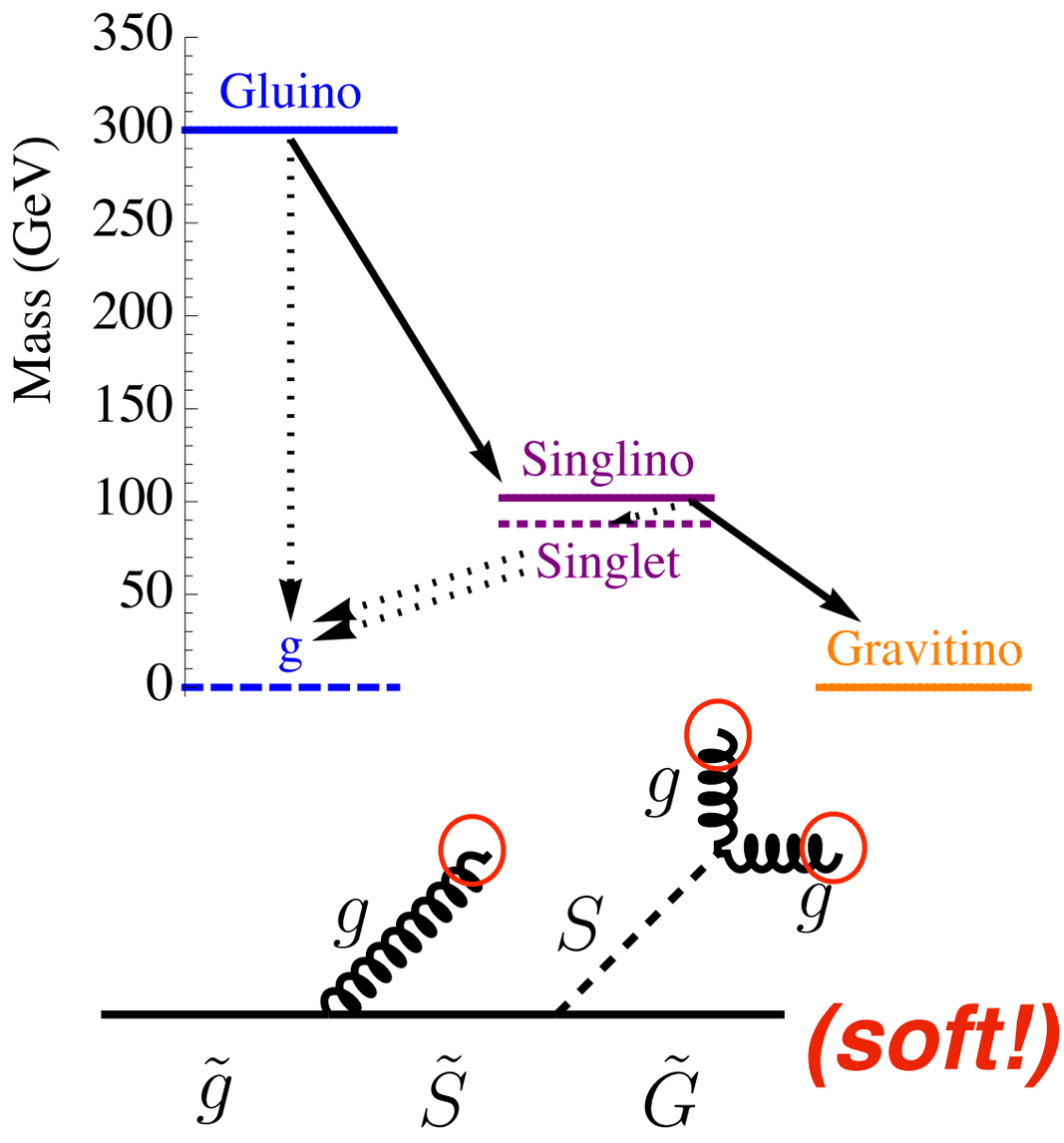
Stealth SUSY

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

- 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.

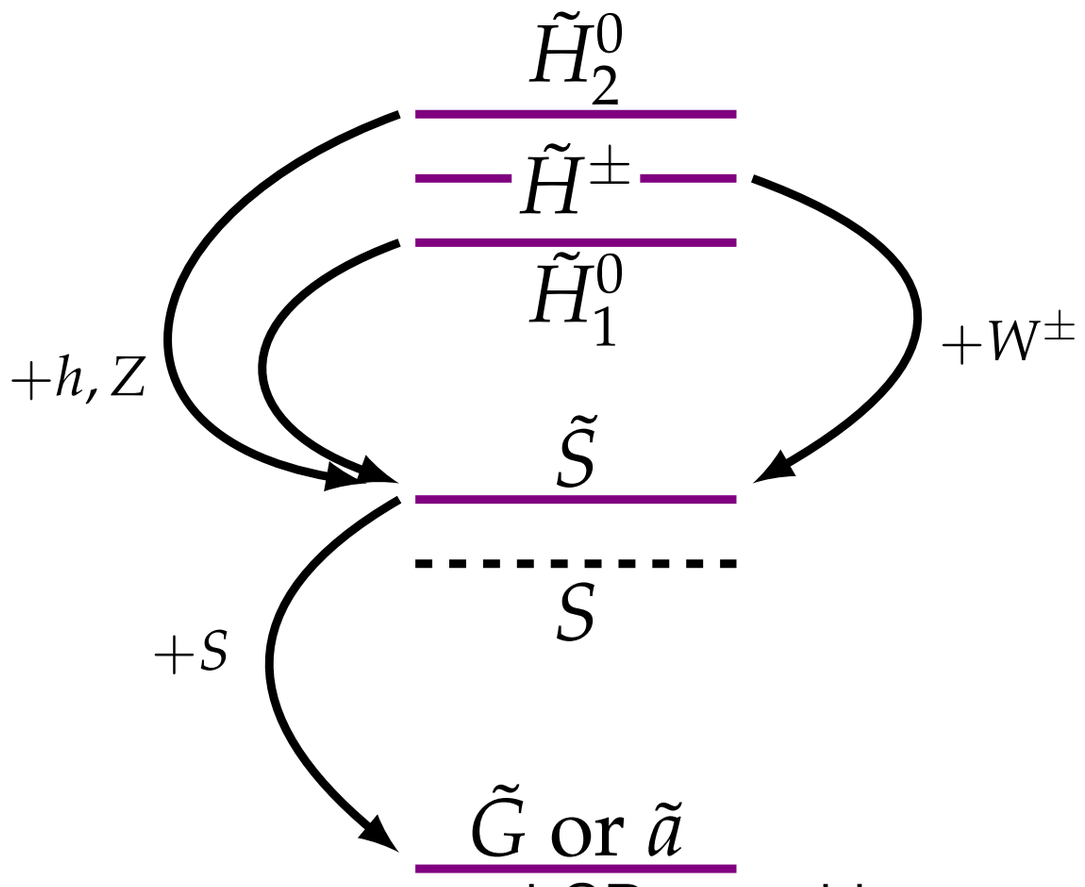
- R-even stealth particles decay back to SM states.

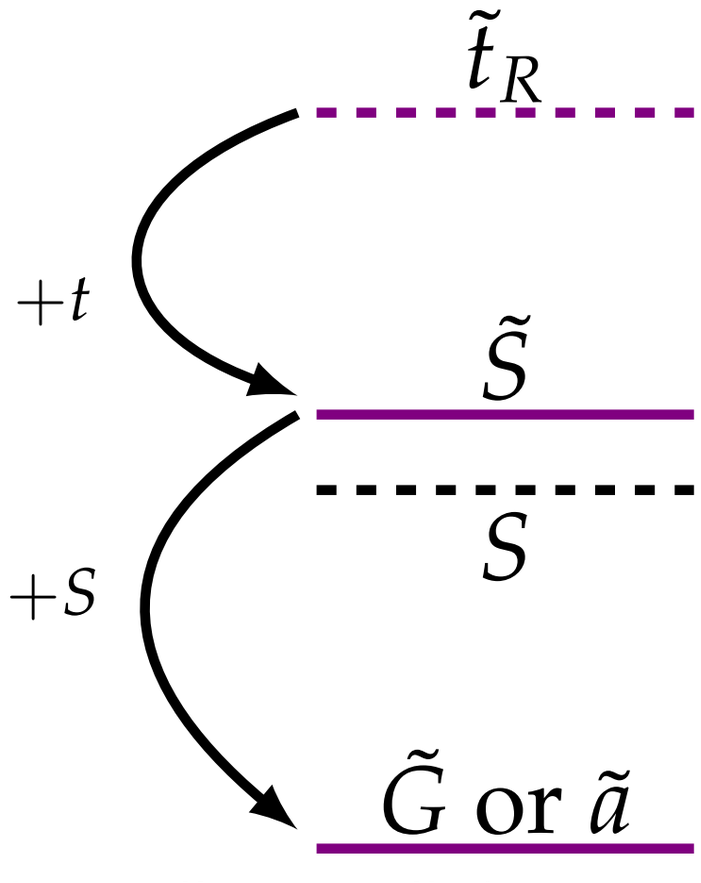


Supersymmetry can hide itself!

LOSP Decay Chains

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

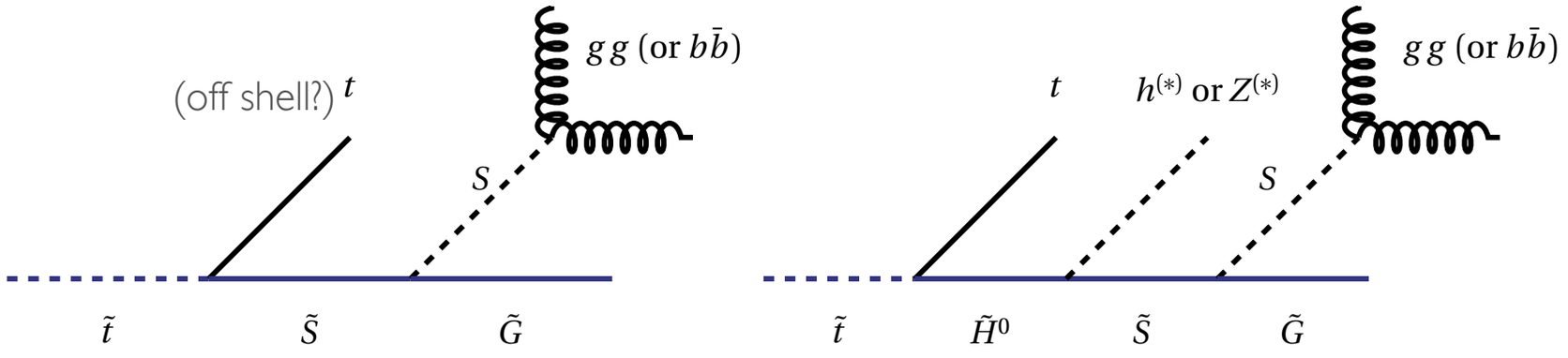




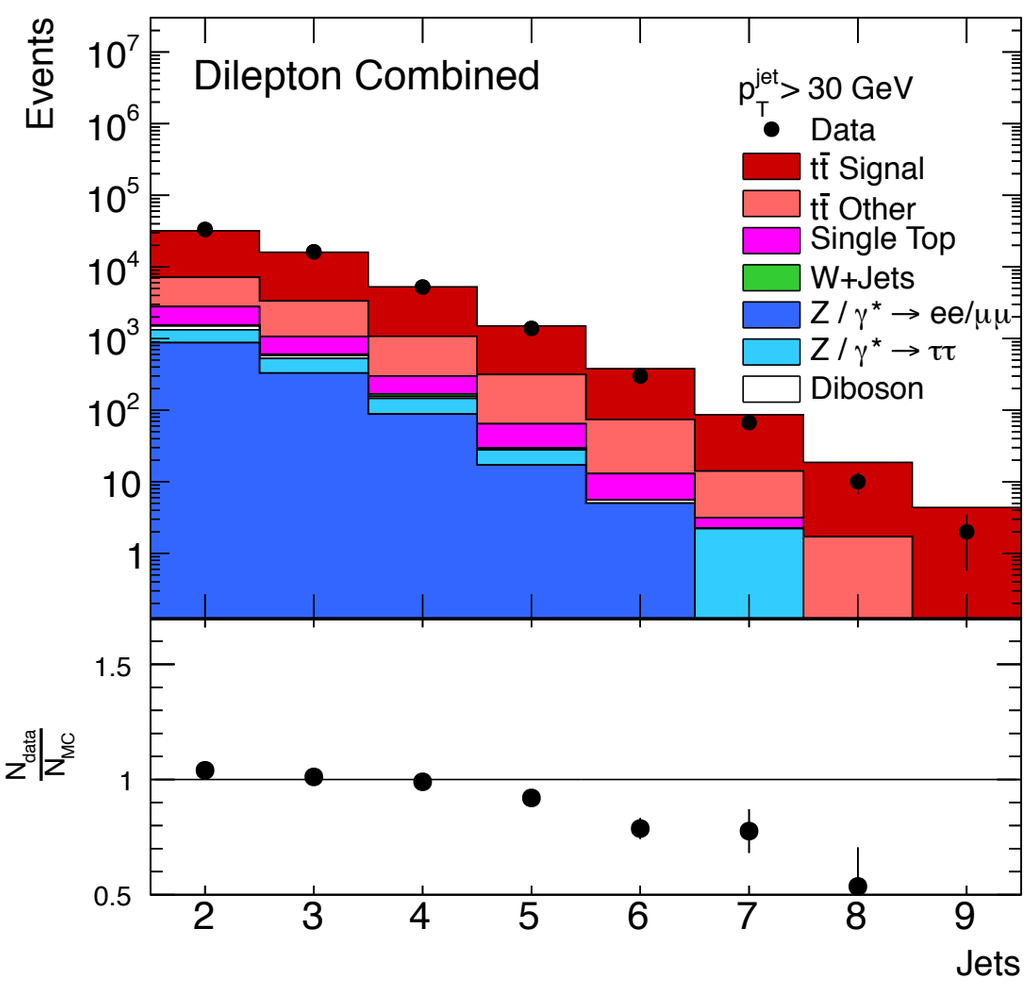
LSP: gravitino or axino. Naturally very light.

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

Stealth SUSY Stops



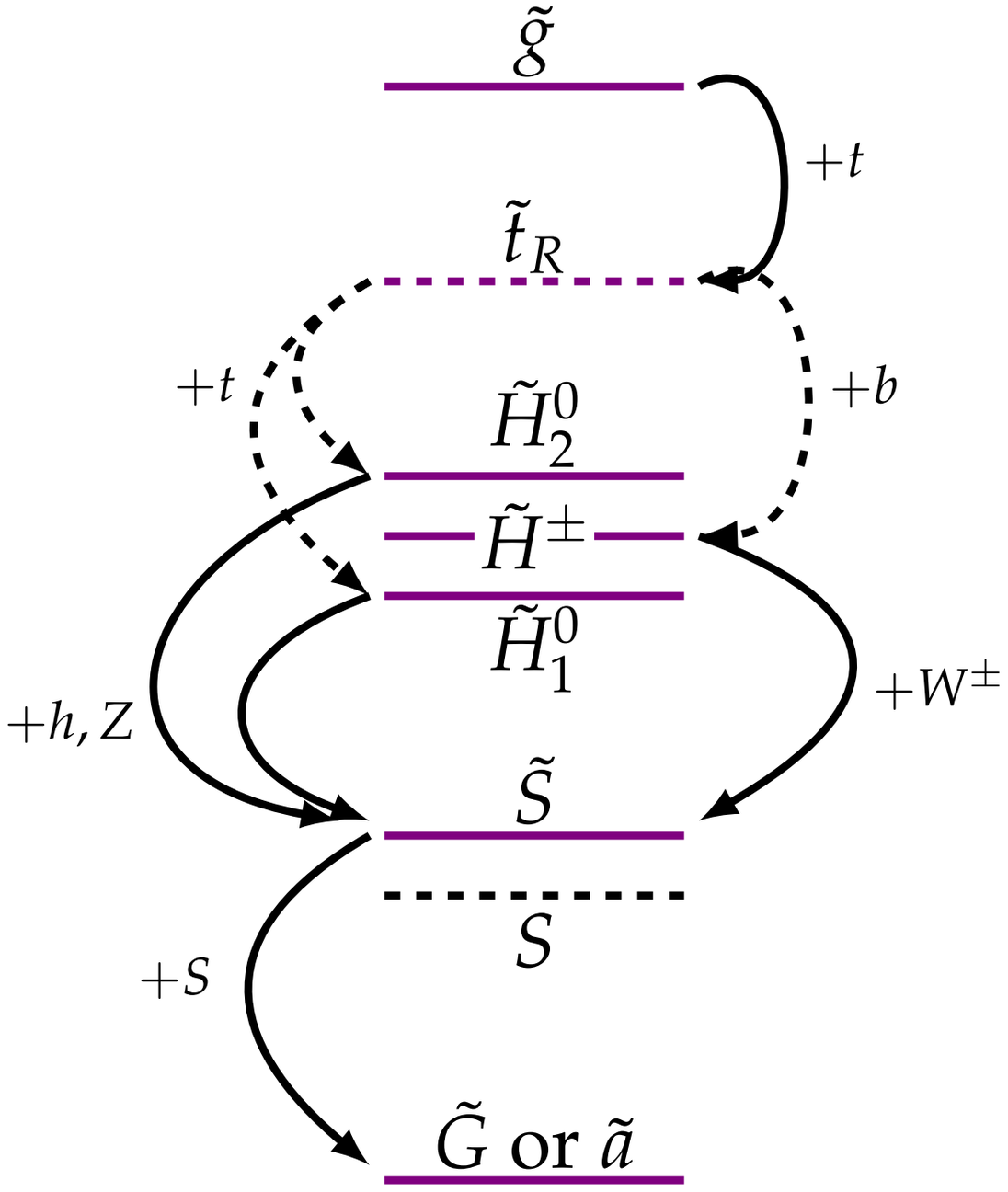
CMS Preliminary, 19.6 fb^{-1} at $\sqrt{s}$ = 8 TeV



Direct stop production in these simplified models is hard to bound with current searches.

Top events with several jets (e.g. this plot from CMS PAS TOP-12-041). **Would like to see direct searches for top events with dijet resonance peaks!**

Gluino Decay Chains

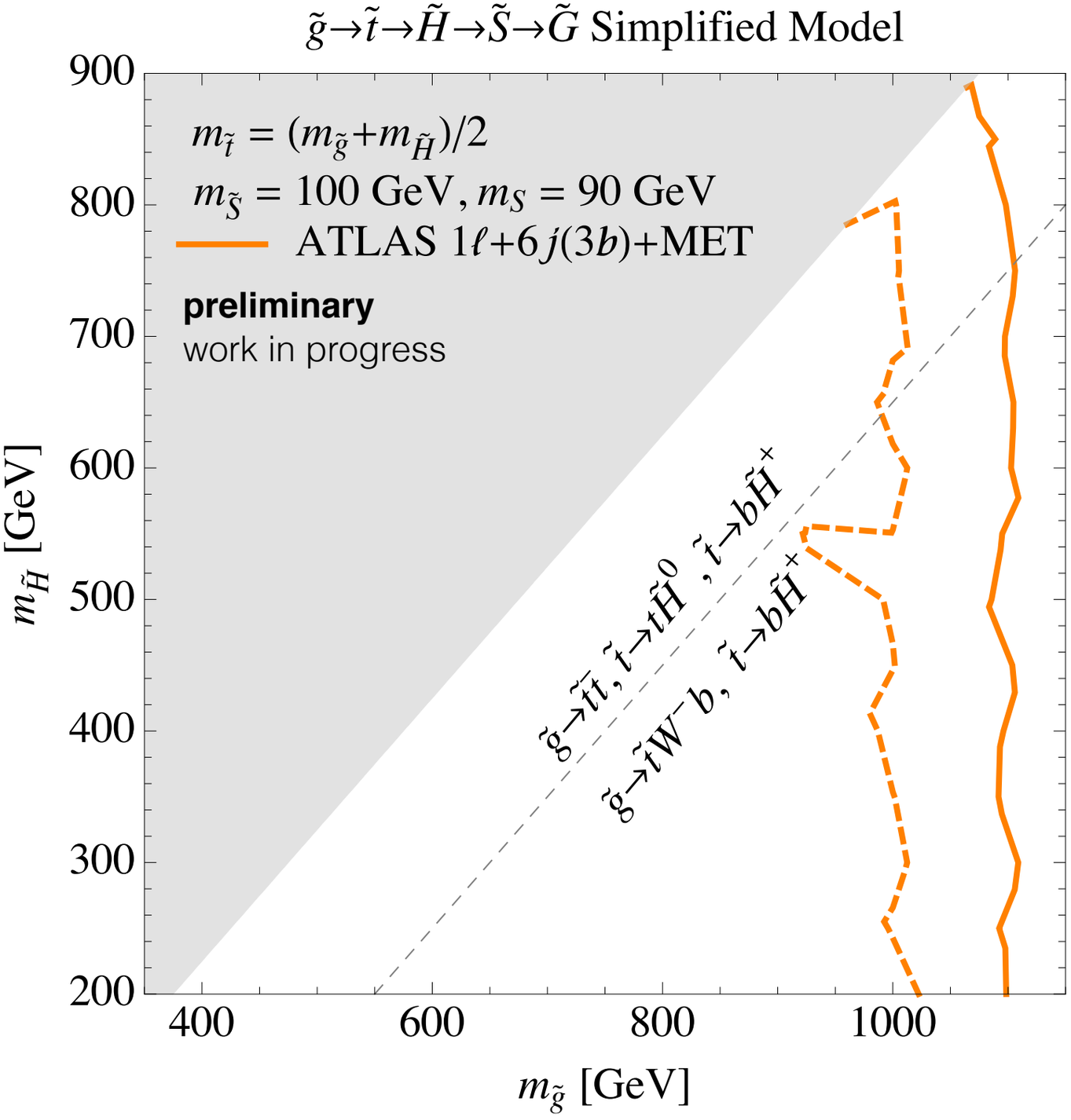


Simplified model. Scripts compute branching ratios. RH stop decays: roughly half t+neutralino, half b+chargino.

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

Stealth Gluino Constraints

Work in progress with JiJi Fan, Rebecca Krall, David Pinner, Josh Ruderman: how much of natural stealthy SUSY survives? Recast existing searches to see.



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

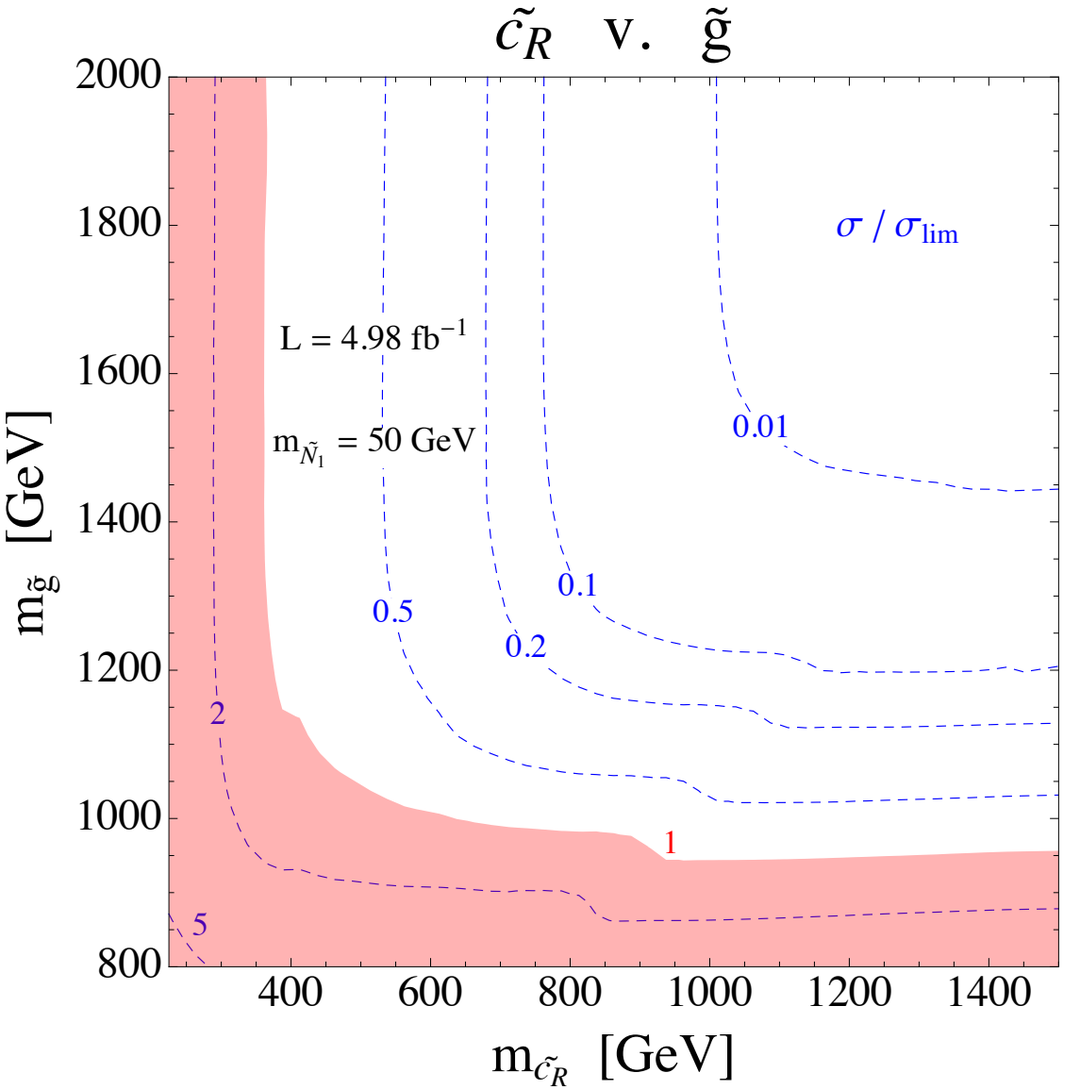
Flavored Naturalness

Allow for mixing among the different squark flavors.

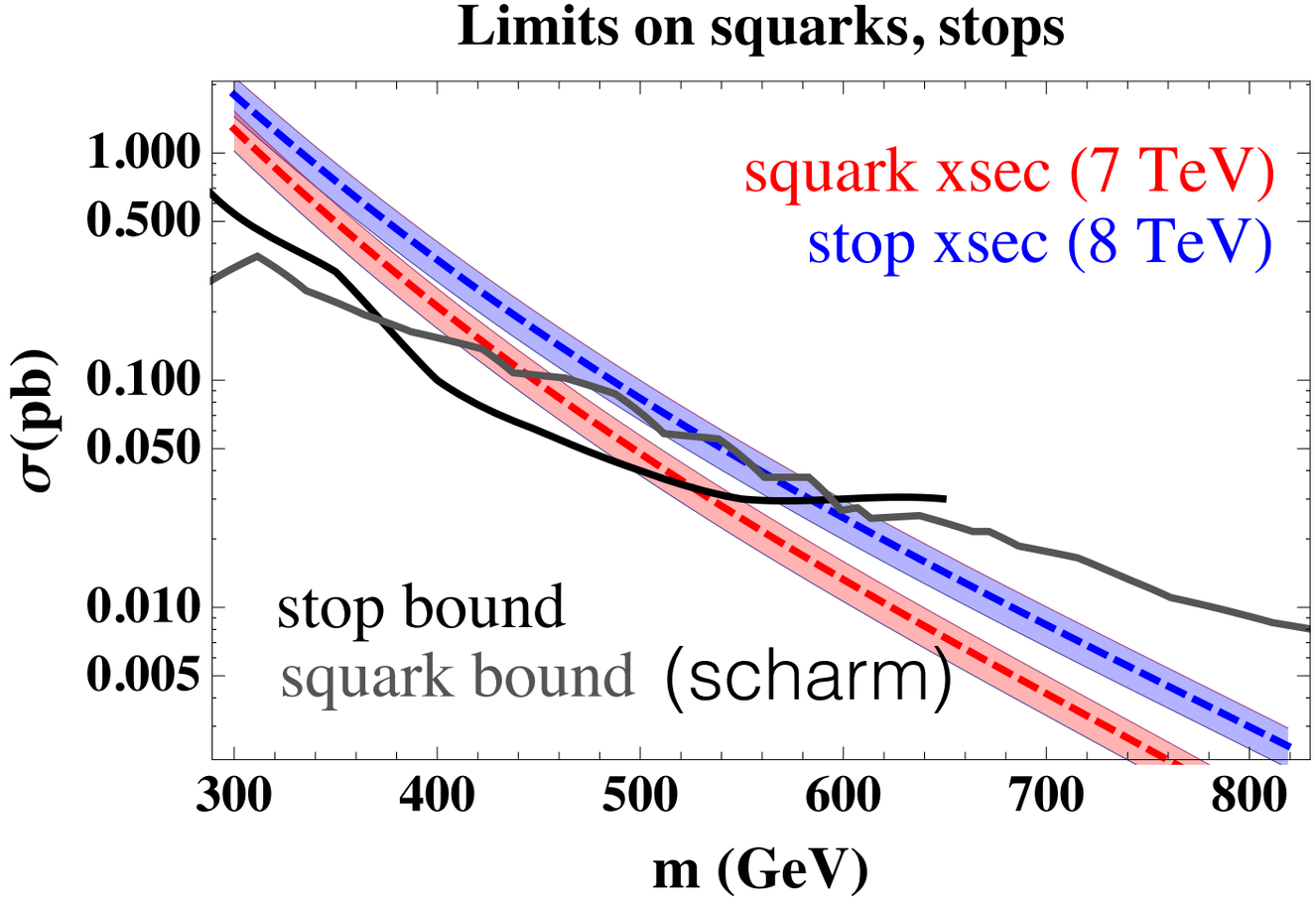
Mahbubani, Papucci, Perez, Ruderman, Weiler 1212.3328
Blanke, Giudice, Paradisi, Perez, Zupan 1302.7232

Second-generation (“scharm”): smaller cross sections than first (no valence production) and less distinct signatures than third (no tops, c-tagging more difficult than b-tagging).

So if the mass and flavor bases aren’t aligned, potentially have weaker limits. Safest from low-energy constraints in RH sector: D-Dbar mixing (Giudice, Nardecchia, Romanino 0812.3610; Gedalia, Grossman, Nir, Perez 0906.1879) $\theta_R^{ut}\,\theta_R^{ct} < 0.01\,(\tilde{m}/500\ \mathrm{GeV})$



Mahbubani et al. 1212.3328

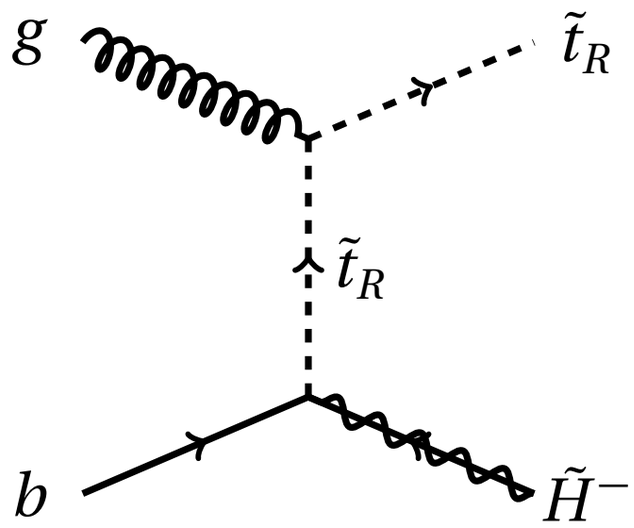


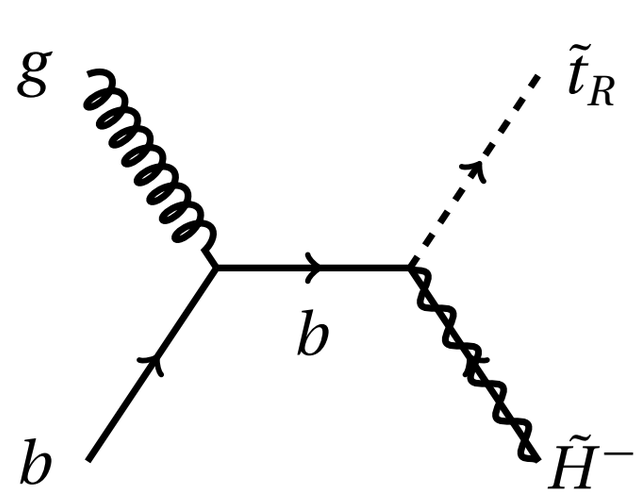
Blanke et al.1302.7232

New signatures: top+charm+MET
same-sign tops if large up squark/stop mixing
D meson observables (CP?)

Mono-top Signals

Recently studied by ATLAS & CMS in dark matter context. Can arise from flavored naturalness (decay to top on one side of event, charm on the other). Also arises in stop-higgsino associated production:





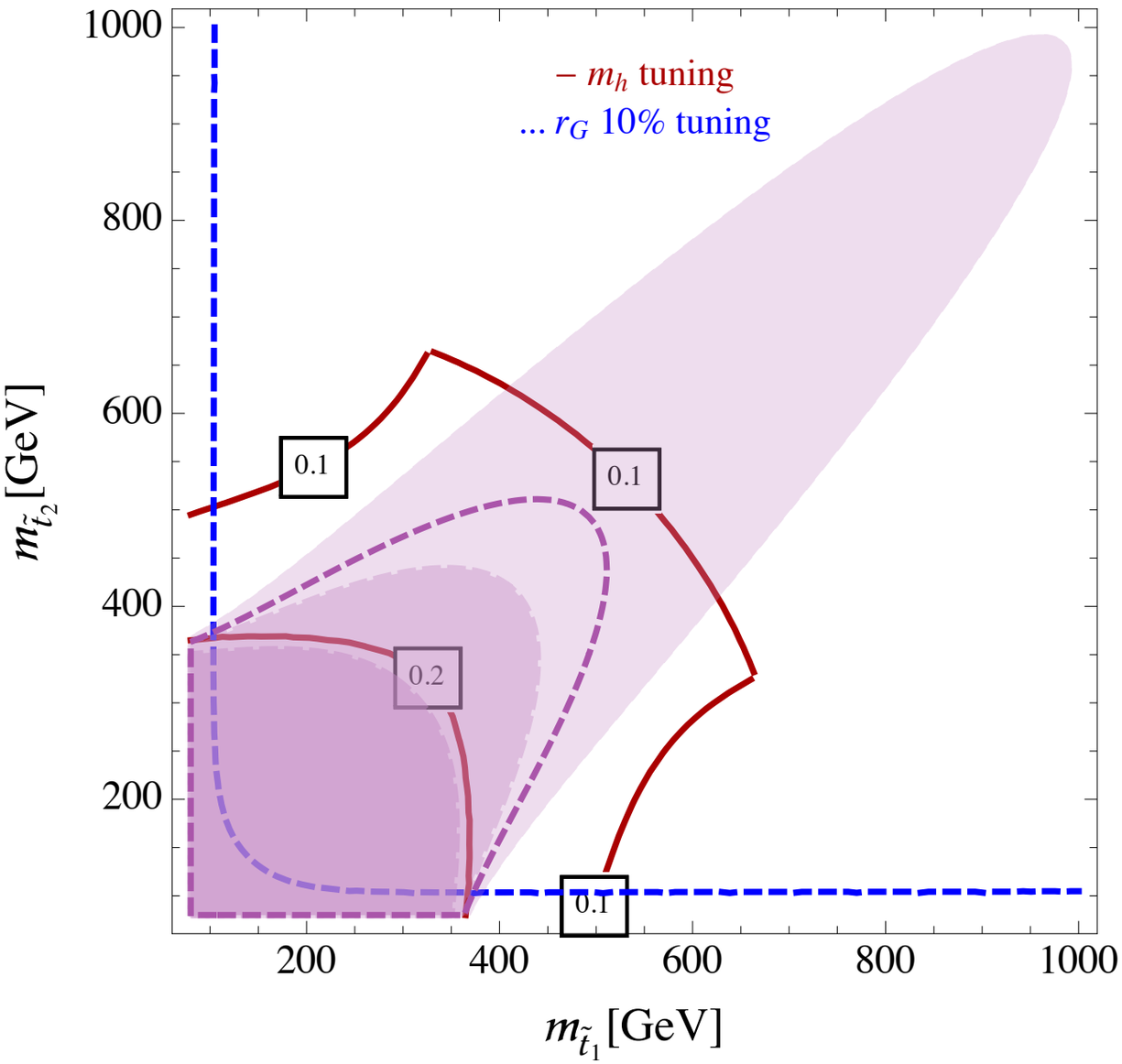
$$W \supset y_t H_u \cdot Q_3 u_3^c \Rightarrow \mathcal{L} \supset y_t \tilde{H}^- b_L \tilde{t}_R$$

Understudied search channel where all couplings are large.

Deserves more attention! *Work in progress with Adam Martin, Felix Yu.*

Higgs Coupling Constraints

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



J. Fan and MR, 1401.7671

Haven't yet updated with latest CMS and ATLAS numbers.

ILC/TLEP/CEPC: reach to stop mass ~ 1 TeV.
Will even get Folded SUSY stops to ~few hundred GeV.

Summary

- LHC Run 1 has put some mild 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