The Status of GMSB Post-Higgs

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SUSY at the Near Energy Frontier, 11.12.13

Higgs and hierarchy

- So far at the LHC, we've discovered a Standard Model-like Higgs boson and nothing else.
- This is certainly a great triumph for the Standard Model, but it only heightens the urgency of the hierarchy problem!
- Null results notwithstanding, SUSY is *still* the best candidate for a solution.
- Gauge mediation is *still* the best way of accommodating all other signposts we have about the nature of UV physics (especially flavor, which is possibly more depressing than LHC null results.).

GMSB Post-Higgs

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2. “Natural SUSY” is (often) GMSB.

Part 1: SUSY Higgs?

The couplings are not a smoking gun; SUSY has a well-defined decoupling limit where the Higgs couplings are SM-like.
(viz. [Azatov, Chang, NC, Galloway '12])

But SUSY in its minimal form predicts $m_h \sim m_Z$ at tree level plus radiative corrections coming from the mismatch between sparticle and particle masses.

The optimist

"126 GeV is within 38% of 91.2 GeV!"

The pessimist

"126 GeV requires one loop effects to be as big as tree level!"

Higgs Mass

If the Higgs quartic couplings are set by MSSM D-terms,
in the limit $m_Z \ll m_A$

$$(X_t \equiv A_t - \mu \cot \beta)$$

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2} \left(\log \left(\frac{M_S^2}{m_t^2} \right) + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12 M_S^2} \right) \right)$$

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Increase the tree-level Higgs quartic (via F-terms, i.e. new singlets; or D-terms, i.e., new gauge forces)

Make the stops heavy (at the price of considerable tuning)

Crank up the threshold correction (via large A-terms)

Brief editorial:

There are many prescriptions for quantifying naturalness, and they can give different answers sensitive to details of the prescriptions. I prefer Veltman's intuitive criterion:

"Radiative corrections are supposed to be of the same order (or much smaller) than the actually observed values."

By this criterion, neither heavy stops nor large A-terms are particularly natural in light of m_h=125 GeV. They're just about at the edge of Veltman's intuitive naturalness. So in my mind, increasing the tree-level quartic is the genuinely natural avenue.

Higgs mass & GMSB

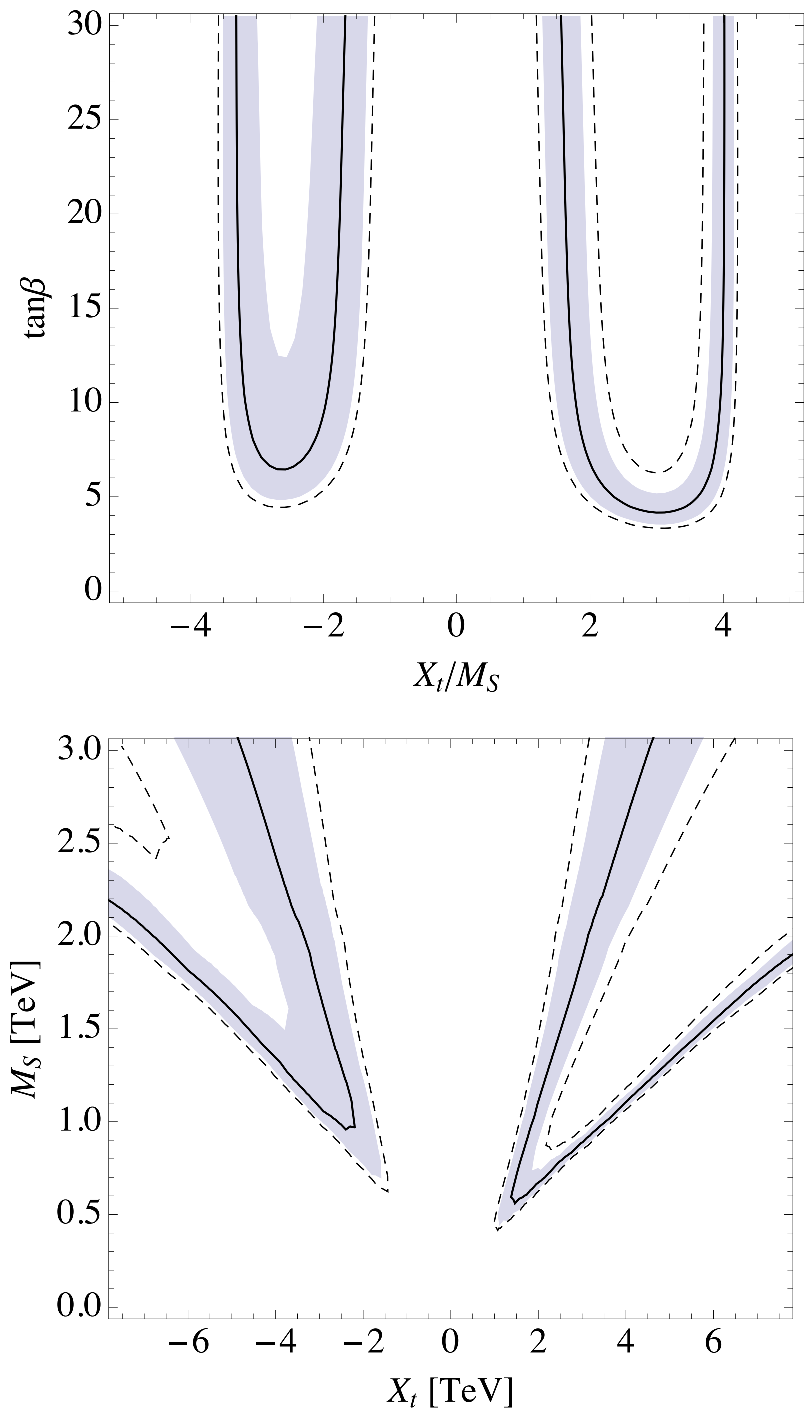
How do the options for the Higgs mass inflect upon GMSB?

1. *Increase tree-level quartic:* nothing particularly unique for GMSB; singlet masses require extra engineering.
2. *Heavy stops:* nothing particularly unique for GMSB, beyond scaling up the sparticle masses.
3. *Large A-terms:* new lessons for GMSB.

Options (1) and (2) don't really force us to shape our expectations for GMSB phenomenology, and can be seen as Higgs mass modules. Option (3) does provide new insight for GMSB phenomenology.

A-terms in GMSB

[Draper, Meade, Reece, Shih '11]



$\tan\beta \gtrsim 3.5 \quad M_S \gtrsim 1\ \mathrm{TeV} \quad |X_t| \gtrsim 2\ \mathrm{TeV}$

- In GMSB, A-terms are suppressed (zero at LO in gauge couplings) at the messenger scale.
- One option is to generate them radiatively from running between the messenger scale and the weak scale.

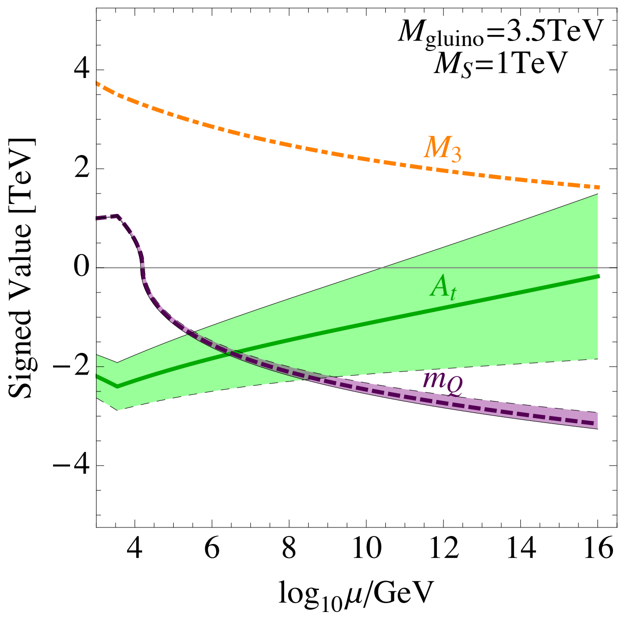
$$\frac{dA_t}{dt} \sim y_t^2 A_t + g_3^2 M_3$$

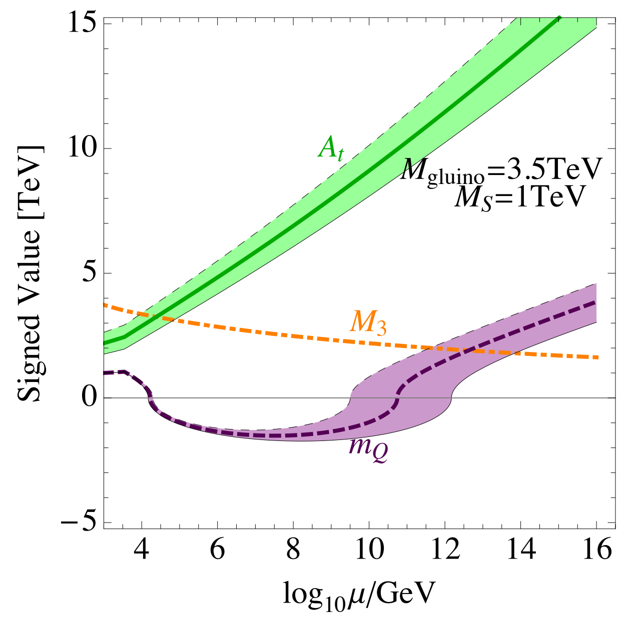
- Another option is to generate them at the messenger scale via new Higgs-messenger interactions.

Both options shape GMSB phenomenology

[Draper, Meade, Reece, Shih '11]

Option 1: A-terms from RGE





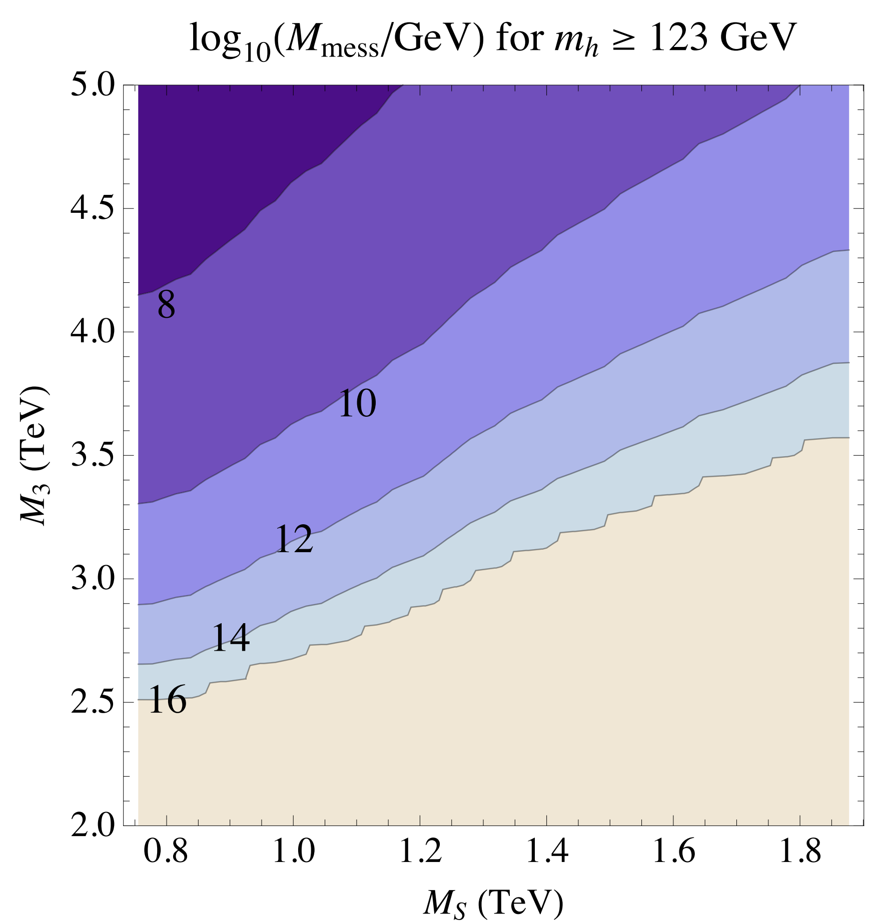
$$\frac{dA_t}{dt} \sim y_t^2 A_t + g_3^2 M_3$$

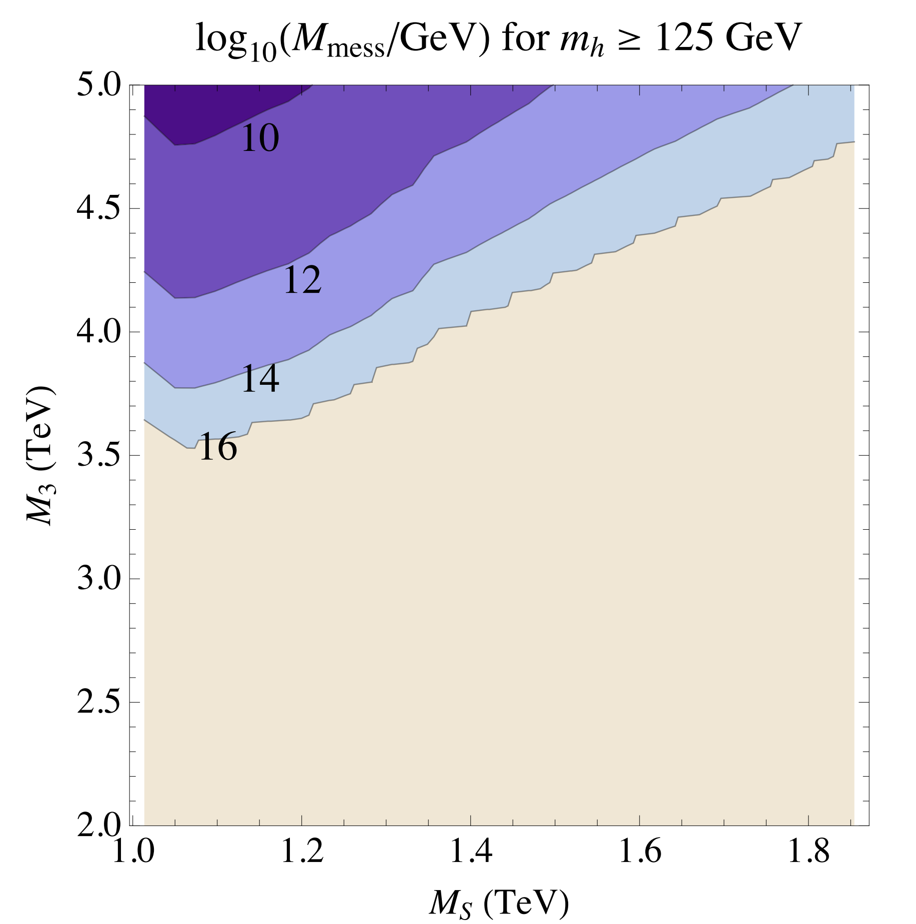
Gluino drives A-terms negative; positive-sign A-terms not viable in GMSB

$$M_3 \gtrsim 3 \text{ TeV}, \qquad M_{mess} \gtrsim 10^8 \text{ GeV}$$

A<0 possible, but forces a high messenger scale, heavy gluinos.

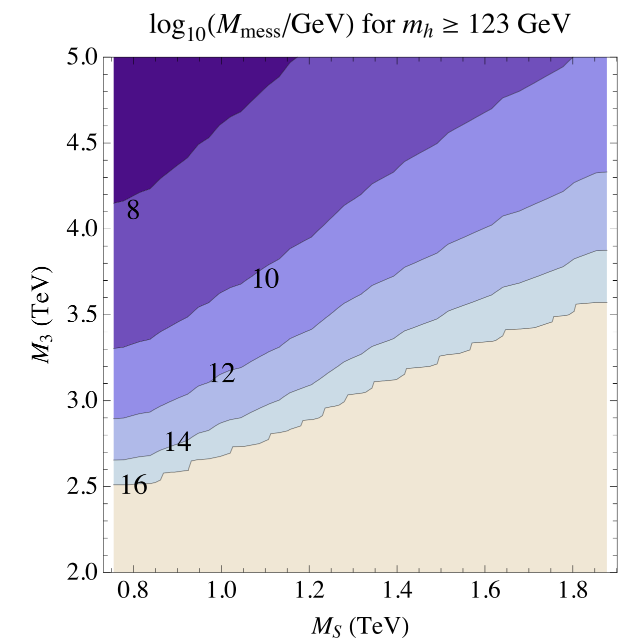
A-terms almost superfluous for naturalness.





Implications for pheno

- Many decades of energy required between M_{mess}, m_W. Implies large *F*, and so (often) detector-stable NLSP. Limits then depend strongly on the NLSP candidate.



$$c\tau_{NLSP} \sim \frac{16\pi^2 F^2}{m_{NLSP}^5} \approx 10 \text{ m} \left(\frac{M_{mess}}{10^8 \text{ GeV}}\right)^2 \left(\frac{200 \text{ GeV}}{m_{NLSP}}\right)^5$$

- Large gluino masses! Consequently, the colored spectrum typically wants to be heavy. Light weak-scale stops require negative squark masses at the messenger scale, which is possible but requires non-minimal GMSB.

- Focus on CHAMPs, R-hadrons, displaced vertices, electroweak production.

[NC, Knapen, Shih, Zhao '12]

Option 2: A-terms at M_{mess}

Alternately, we could try to generate parametrically large A-terms at the messenger scale. Requires coupling GMSB messengers to MSSM fields.

You typically want to do this by coupling to the Higgs doublets, since this gives A-terms aligned with the Yukawas (flavor problems otherwise):

Given a model that induces $K \supset \frac{X^\dagger}{M} H_u^\dagger H_u$ and given $W \supset \lambda_{ij} H_u Q_i \bar{u}_j$

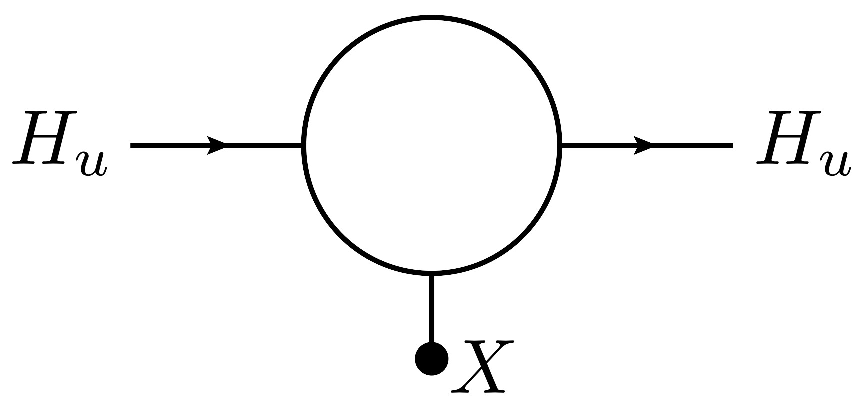
Integrating out auxiliary components yields $\rightarrow \mathcal{L} \supset \lambda_{ij} \frac{F_X^\dagger}{M} H_u \tilde{Q}_i \tilde{\bar{u}}_j + \frac{|F_X|^2}{M^2} |H_u|^2$

N.B., also inevitably get a Higgs soft mass $m_H^2 \propto A^2$

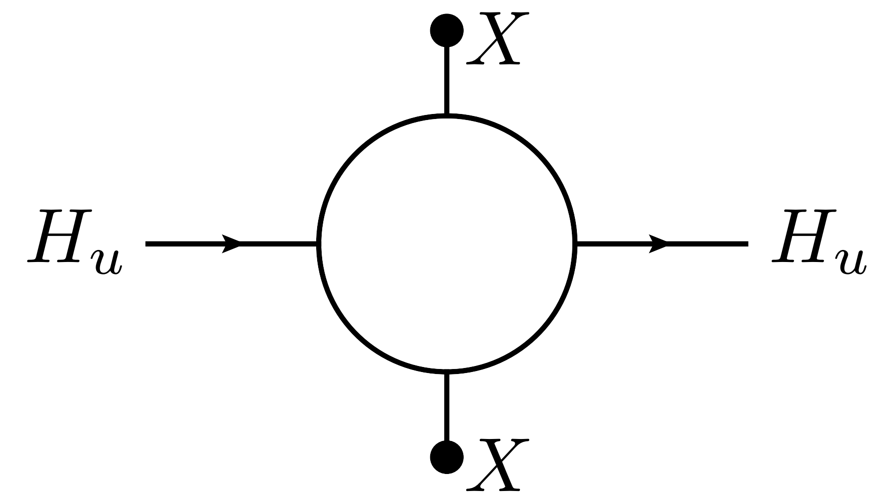
Can get this from a theory with Higgs-messenger couplings $\delta W = \lambda_{uij} H_u \Phi_i \tilde{\Phi}_j + \lambda_{dij} H_d \Phi_i \tilde{\Phi}_j$

The A/m_H^2 problem

Diagrammatically, the A-terms come from diagrams like...



...but you also get one-loop Higgs soft masses,



This is phenomenological disaster, m_H^2 too large. Reminiscent of the **μ**/B**μ** problem; we call this the A/m_H^2 problem

But unlike **μ**/B**μ**, the A/m_H^2 problem can be uniquely solved by the $U(1)_R$ symmetry of minimal gauge mediation (a la Dine, Nelson, et al. '93-'95, $\langle X \rangle = M + F_X \theta^2$)

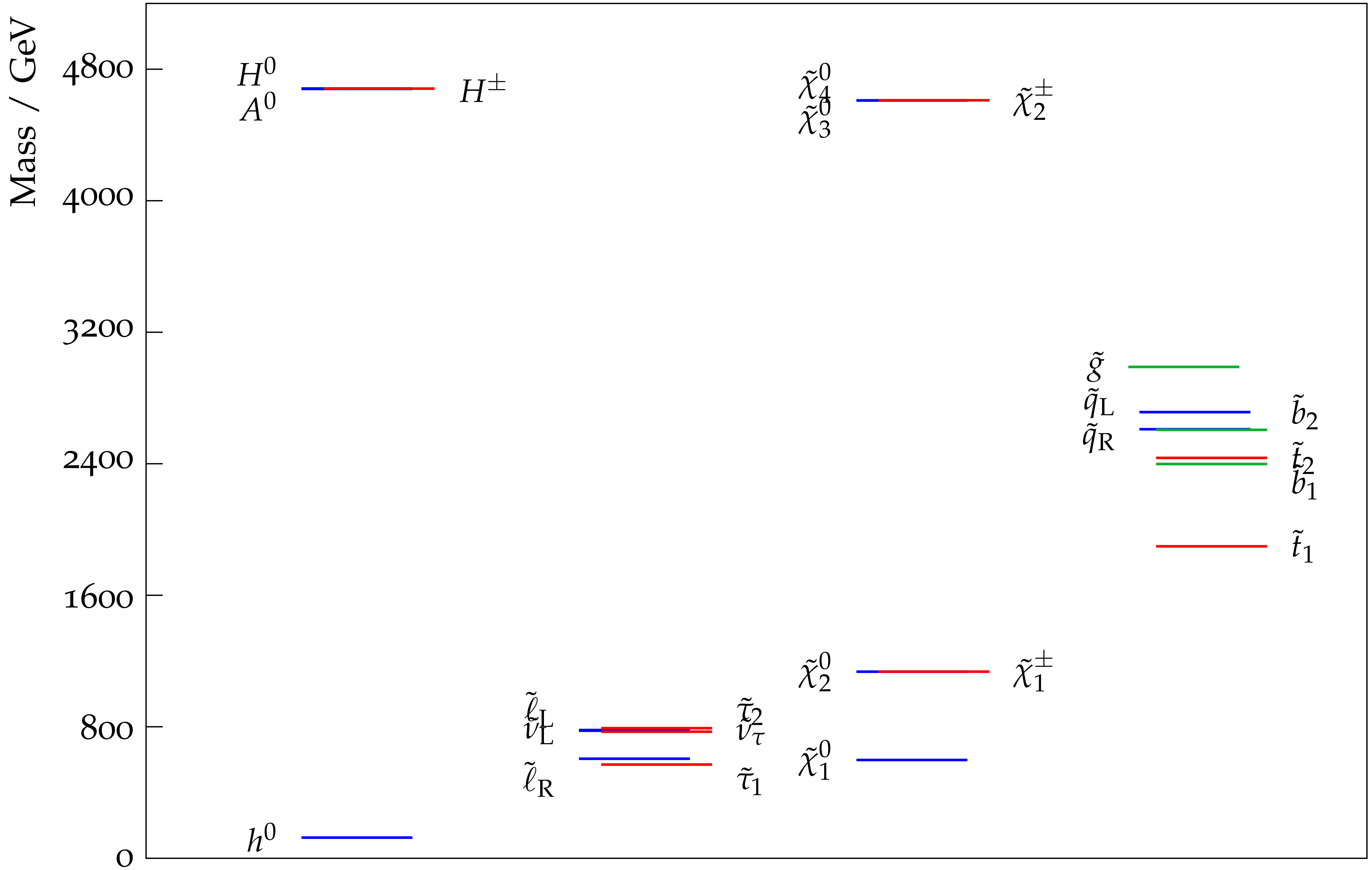
(This is slightly amusing, after years of general gauge mediation.)

The upshot

- Can construct models that work, generating sufficiently large A-terms without (big) A/m_H^2 problem. Can even make NMSSM-type models work, explaining origin of **μ**/B**μ**
- However, still have the "little" A/m_H^2 problem, i.e., $m_H^2 \propto A^2$
- This tells us that the soft masses m_H^2 are guaranteed to be large, and so **μ** must also be large. This means higgsinos are heavy and the tree-level naturalness of the theory is imperiled to the order of 0.1% tuning.
- So we can construct models with large A-terms at the messenger scale, but in the process we discover that we could have just stayed home and explained the Higgs mass with heavy stops (the only edge is LHC-accessible states).

Implications for pheno

Heavy higgsinos, inevitably stau NLSP. But tuning is ~0.1% at best.
Works best for low messenger scales, so prompt NLSP.



Λ = 110 TeV
M = 220 TeV
λ_u = 1.1

stops significantly lighter than other squarks

stau NLSP

Part 1 Summary

- A-term explanations are challenging to realize in GMSB, either via running or via new interactions. Often no more natural than simply having heavy stops, but admits LHC-accessible states.
- The most natural solution entails additional physics (singlet, gauge bosons, etc.), implying extensions of the MSSM at low energies.
- But there is no inviolate rule about allowed NLSP or GMSB signals. So keep on keeping on, and don't worry too much about m_h=125 GeV.

Part 2: Natural SUSY is (often) GMSB

We typically factorize "natural SUSY" simplified models from "GMSB". But...

Two powerful reasons for natural SUSY to be low-scale:

- Need to make stops light but keep flavor protection for first two generations. Most easily accomplished in GMSB-based models.
- Need to lower the radiative cutoff to avoid linking gluino, stop masses too closely.

Even if the models are not precisely GMSB, they often have a goldstino at the bottom of the spectrum. Signals are GMSB-esque.

Two examples

1. "Split families": SUSY breaking is communicated by gauge mediation plus a 4D version of gaugino mediation.

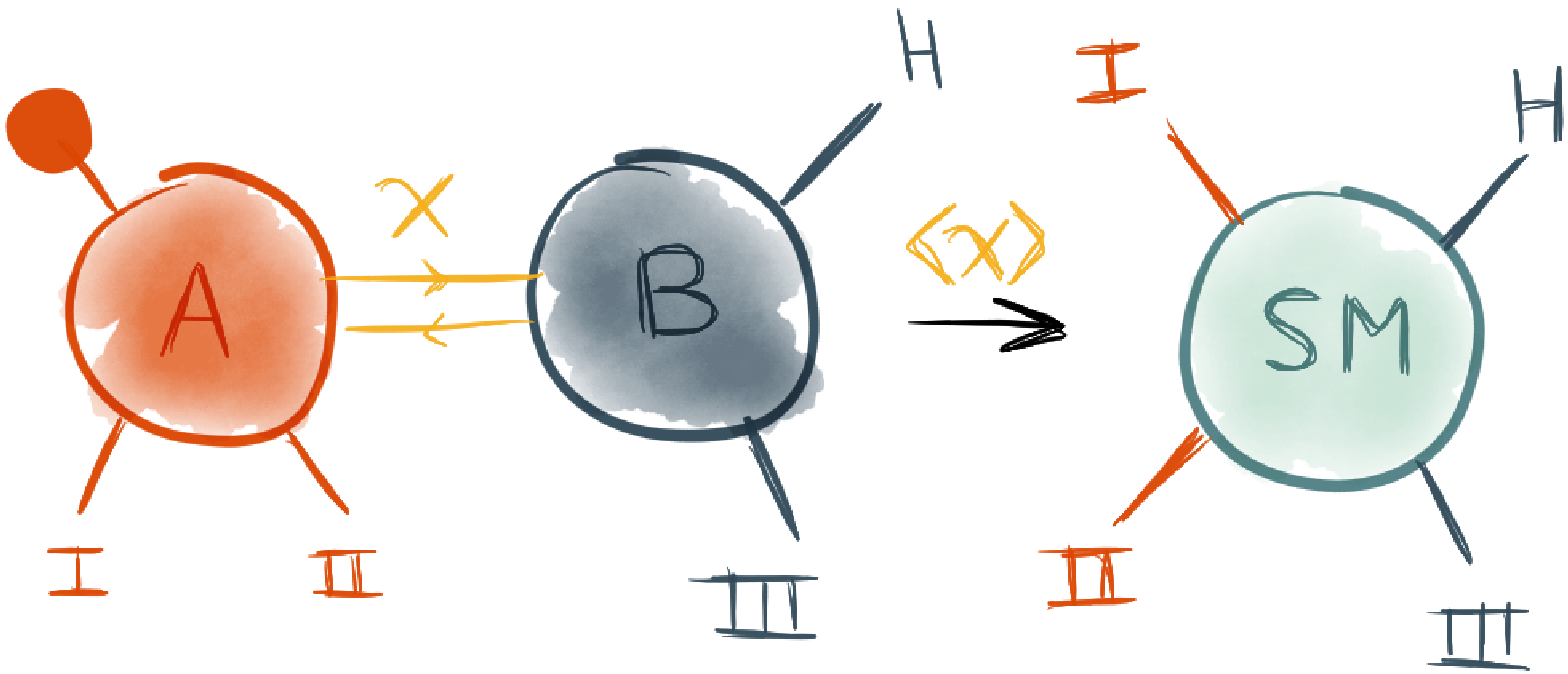
2. "Flavor mediation": SUSY breaking is communicated by a gauged flavor symmetry. Gauge mediation, just not via SM gauge bosons.

[NC, Green, Katz '11; NC, Dimopoulos, Gherghetta '12]

Split families

- Imagine that the first two generations are charged under a different set of Standard Model gauge groups at high energies.
- Above some scale f, the SM gauge group is extended into a double copy, $[SU(3)\times SU(2)\times U(1)]_A \times [SU(3)\times SU(2)\times U(1)]_B$
- First two generations transform under A copy, third generation and Higgs doublets under the B copy.
- SUSY breaking is transmitted by gauge mediation to the A copy.
- Goldstino is at the bottom of the spectrum, followed by third-generation sparticles. RH stau is typically the NLSP, but stop/sbottom also light.

Split families



Link fields χ higgs to the diagonal gauge group at a scale f.
Spectrum for first two generations is gauge mediation; spectrum for third generation is (deconstructed) gaugino mediation.

Split families

- There is an approximate theory of flavor, since not all Yukawa couplings can be marginal:

$$W \supset HQ_3\bar{u}_3 + \frac{1}{M}\chi HQ_3\bar{u}_i + \frac{1}{M^2}\chi^2 HQ_i\bar{u}_j$$

- The third generation soft masses are much smaller than the first two, and the first two enjoy a U(2) sflavor symmetry, so no FCNC problems!

$$\tilde{m}_i^2 \sim \left(\frac{\alpha_i}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2 \gg \tilde{m}_3^2 \sim \left(\frac{\alpha_i}{4\pi}\right)^2 \left(\frac{f}{M}\right)^2 \left(\frac{F}{M}\right)^2$$

Split families

- The Higgs mass prediction is automatically raised because there are new contributions to the D-term due to the extended gauge symmetry:

$$\delta m_h^2 = \frac{g_A^2}{g_B^2}\frac{m_S^2}{m_V^2 + m_S^2} m_Z^2 \cos^2(2\beta)$$

- There is a low cutoff f~10 TeV to the radiative contributions to the Higgs soft mass. Tuning is improved, gluino can be twice as heavy as the stops:

$$\delta m_{\tilde{t}}^2 = \frac{2g_s^2}{3\pi^2} m_{\tilde{g}}^2 \ln\left(f/m_{\tilde{g}}\right)$$

[NC, McCullough, Thaler '12]

Flavor mediation

A different flavor of gauge mediation.

Imagine a U(1) gauge group broken spontaneously at a scale f which also gauge-mediates SUSY breaking via messengers

$$\langle X \rangle = M + F\theta^2 \qquad\qquad W \supset X\Phi_+\Phi_-$$

When $f > M$, the effects of SUSY breaking are parametrically suppressed:

$$\tilde{m}^2 \sim \begin{cases} \left(\frac{M}{f}\right)^2 \left(\frac{\alpha_i}{4\pi}\right)^2 \frac{F^2}{M^2} & M \ll f \\ \left(\frac{\alpha_i}{4\pi}\right)^2 \frac{F^2}{M^2} & f \ll M \end{cases}$$

N.B., these effects even exist in vanilla GMSB due to m_W, m_Z

Flavor mediation

Generalizes readily to non-abelian groups, where the spectrum depends on the pattern of breaking. Can get hierarchical breaking proportional to gauge boson masses:

$$\left(\widetilde{m}_q^2\right)_{ij} = C(\mathbf{\Phi})\frac{\alpha_F^2}{(2\pi)^2}\left|\frac{F}{M}\right|^2 \sum_a f(\delta^a)\,(T_q^a T_q^a)_{\{ij\}}, \qquad \delta^a \equiv \frac{M_V^{a\,2}}{M^2}$$

How can we use this?

Gauge the simplest non-abelian flavor symmetry of the Standard Model without mixed anomalies:

$SU(3)_F$ with Q, U^c, D^c, L, E^c all fundamentals

	$\boldsymbol{Q}$	$\boldsymbol{U^c}$	$\boldsymbol{D^c}$	$\boldsymbol{L}$	$\boldsymbol{E^c}$	$\boldsymbol{H_u}$	$\boldsymbol{H_d}$	$\boldsymbol{N^c}$	$\boldsymbol{S_u}$	$\boldsymbol{S_d}$
$\mathrm{SU}(3)_F$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{6}}$	$\bar{\mathbf{6}}$

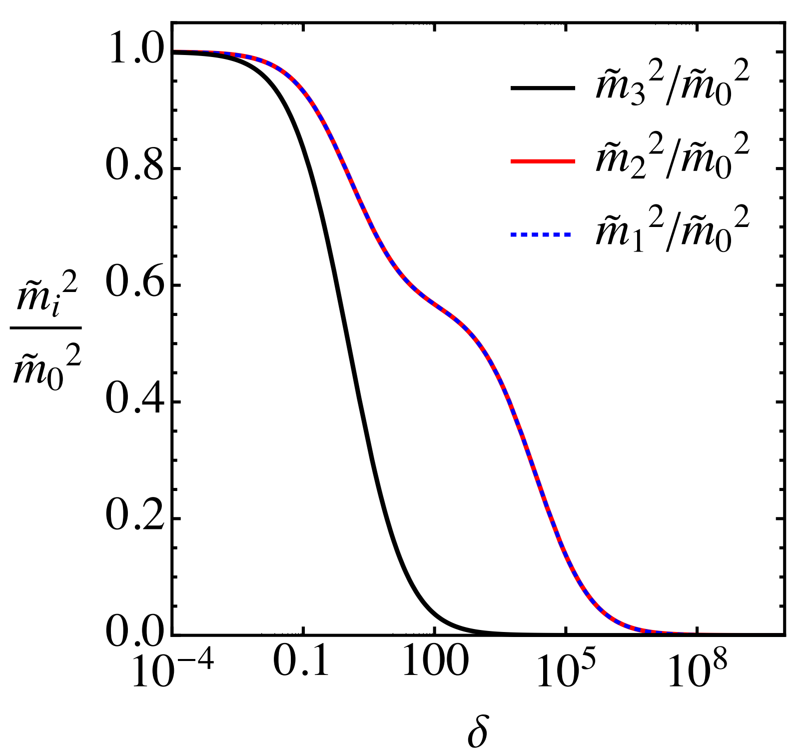
Breaking the symmetry

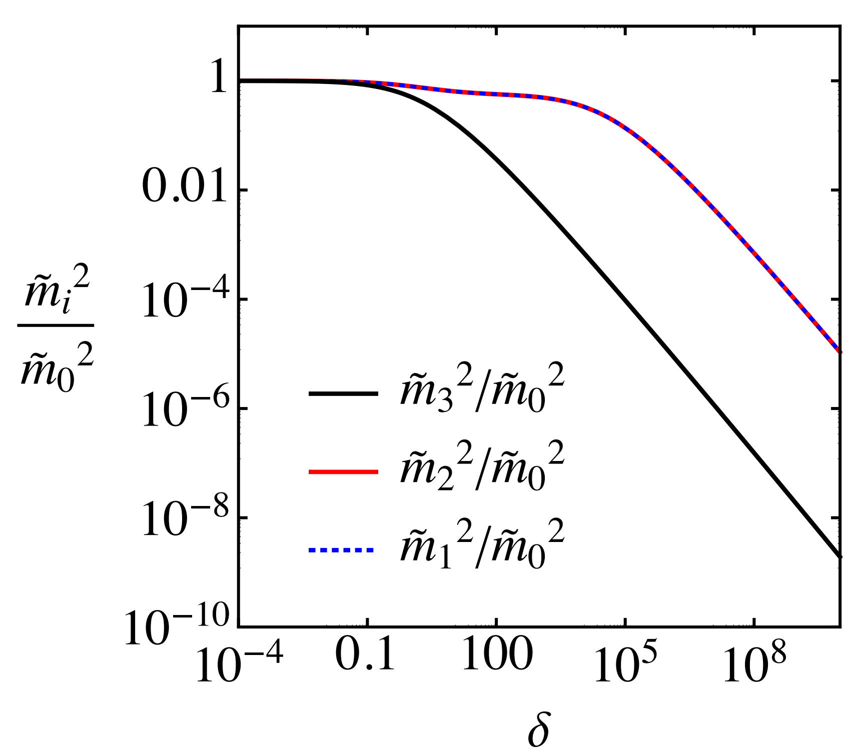
Spontaneously break $SU(3)_F$ to generate SM Yukawas.
E.g., with two symmetric tensors S_u, S_d

$$W = \frac{1}{M_{S_u}} \mathbf{S_u H_u Q U^c} + \frac{1}{M_{S_d}} \mathbf{S_d H_d Q D^c},$$

$$\langle \mathbf{S_u} \rangle = \begin{pmatrix} v_{u1} & 0 & 0 \\ 0 & v_{u2} & 0 \\ 0 & 0 & v_{u3} \end{pmatrix} \qquad \langle \mathbf{S_d} \rangle = V_{\rm CKM} \begin{pmatrix} v_{d1} & 0 & 0 \\ 0 & v_{d2} & 0 \\ 0 & 0 & v_{d3} \end{pmatrix} V_{\rm CKM}^T$$

This breaking gives Yukawa couplings and spectrum of flavor gauge bosons.
GB mass spectrum is *correlated* with Yukawas. So MSSM soft spectrum is *anti-correlated*.



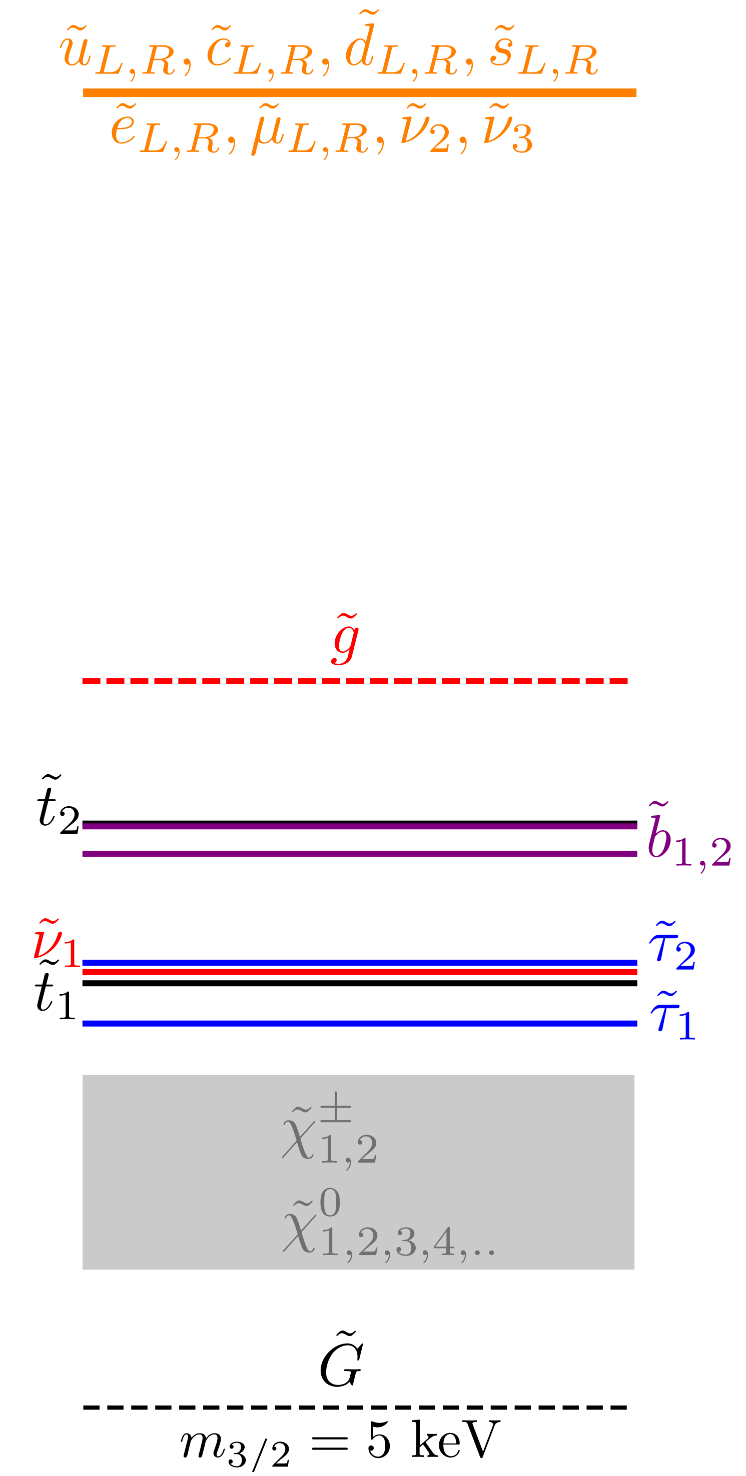


There is a *U(2)* sflavor symmetry from *SU(3)* > *SU(2)* > nothing

So light 3rd generation sfermions, heavy 1st/2nd generation sfermions. But this is still "gauge mediation"

Flavor phenomenology

- Of course, this is not a complete model; need Higgs sector parameters (as in GMSB) and MSSM gaugino masses (but natural for standard GMSB to coexist). These details control nature of the NLSP.
- But as in standard GMSB, the goldstino is light and signals are GMSB-like.
- NLSP is typically higgsino or stau, though bino, stop NLSP are possible. *F* can cover the usual range of possibilities (prompt/displaced/collider-stable).



Implications for pheno

- Of course, GMSB already had "natural SUSY" signals (e.g., stau/higgsino NLSP), but often with universal squark/gluino production. Likewise, other 3rd-generation NLSPs, cascades are both interesting.
- There is some coverage of "natural GMSB" cascades at LHC already --e.g. ATLAS "NGM", CMS "natural Higgsino NLSP" searches, focused on tau/Z final states. *(Ask me offline for a natural model with heavy higgsinos.)*
- But there are new topologies to consider. For example, a stop-bino simplified model with final state **$t\bar{t}+\gamma\gamma$+MET**. To my knowledge this is not (optimally) covered at ATLAS or CMS. This is just one hole; I am optimistic we can collectively come up with more ideas for new searches. E.g., natural production plus displaced NLSP decay?

Part 2 Summary

- Natural SUSY is the subject of considerable focus, and we typically treat this as distinct from GMSB. But genuine models for "natural SUSY" often have low-scale SUSY breaking for reasons of flavor and radiative naturalness.
- So there is a whole class of motivated spectra whose signals could be characterized as "natural GMSB".
- This motivates new(ish) natural SUSY possibilities: all your favorite "natural" spectra with gravitino LSP (& bino often still light).
- Much of this is already covered by GMSB/natural searches, but we should think hard about whether there is something we've missed ($t\bar{t}+\gamma\gamma$+MET? longer natural+GMSB cascades?).

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1. Higgs properties tell us that GMSB is doing fine for the purposes of LHC searches. The purely MSSM case is under strain, but MSSM extensions are in reasonable shape. Explanations for the Higgs mass often correlate with the NLSP type, but all types are still motivated. *Keep pushing!*

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2. "Natural SUSY" is (often) GMSB-like -- for good reasons! -- and we should think carefully about whether this gives new natural SUSY signals & searches at the LHC. This also renders existing GMSB searches more relevant than ever.

Thank you!