Theories of Natural Supersymmetry

Nathaniel Craig (Rutgers & IAS)

Based on work with
Daniel Green (IAS) & Andrey Katz (Harvard) *arXiv: 1103.3708*
Savas Dimopoulos (Stanford) & Tony Gherghetta (Melbourne) *arXiv: 1203.0572*
Matthew McCullough & Jesse Thaler (MIT) *arXiv: 1201.2179 & 1203.1622*

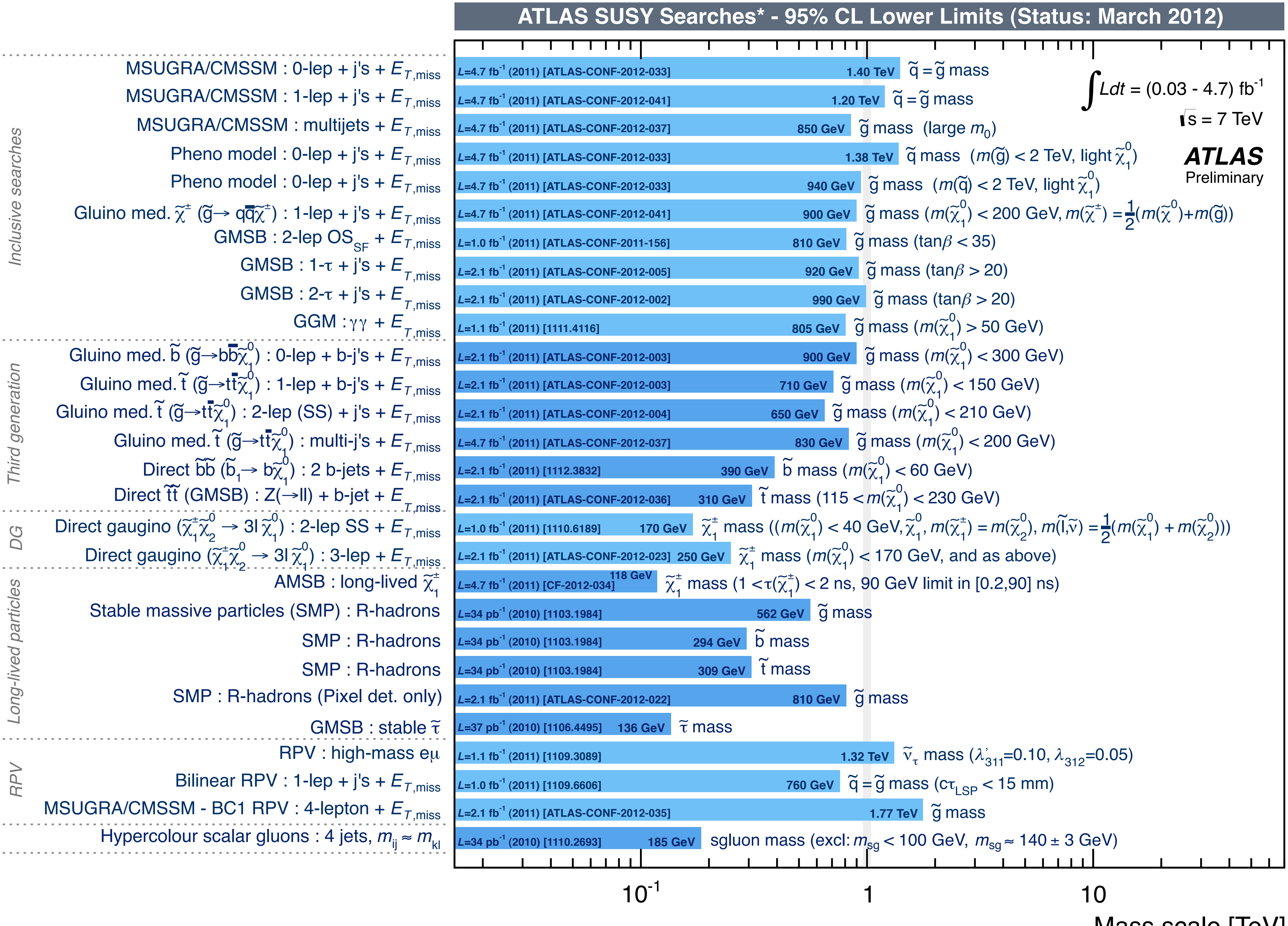
Planck 2012

So...supersymmetry?

On one hand, thus far there is no evidence for SUSY at the LHC.

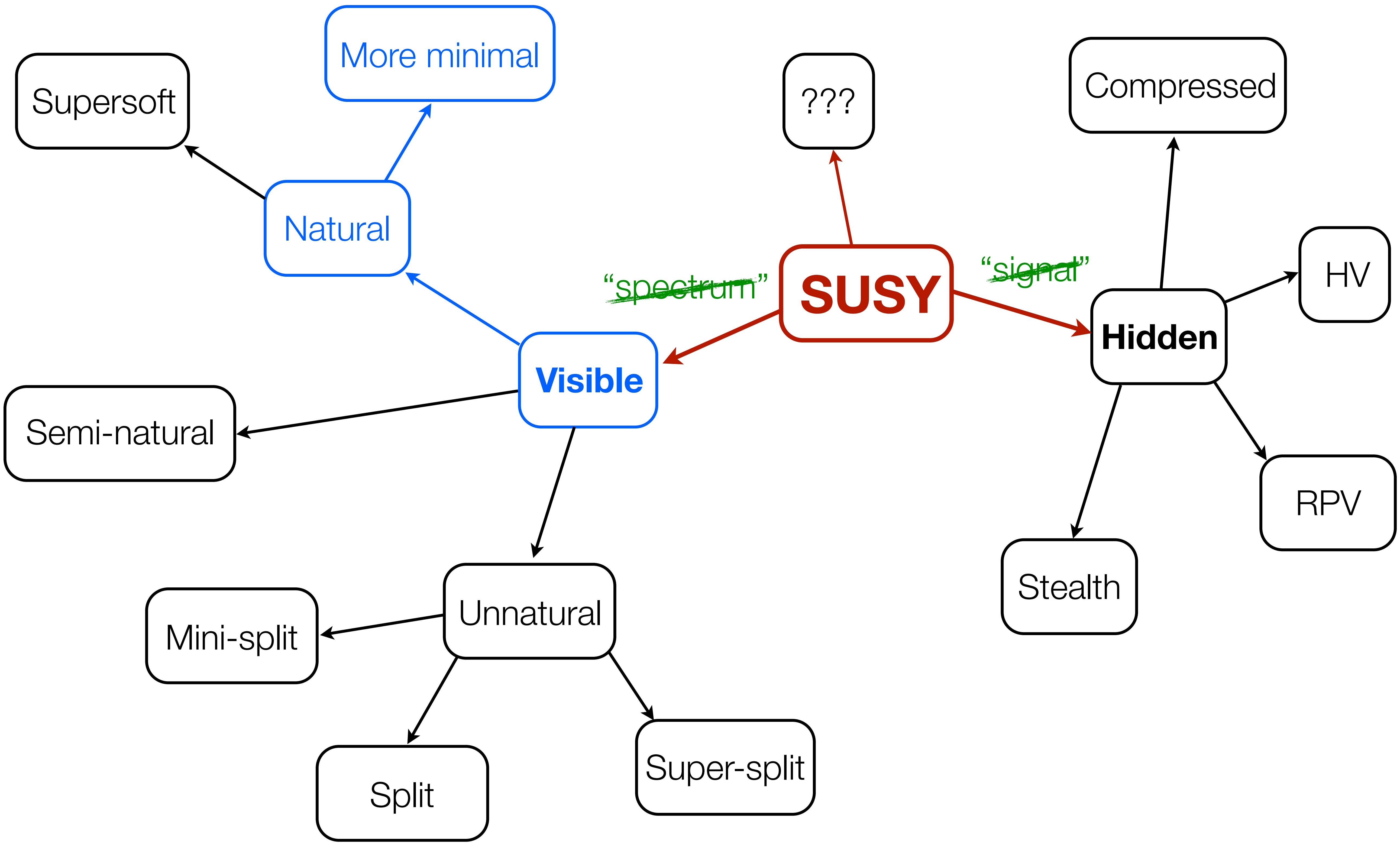
On the other hand, a Higgs at ~125 GeV really wants to be supersymmetric (within 30% of the Z mass!)

So let's not give up just yet...



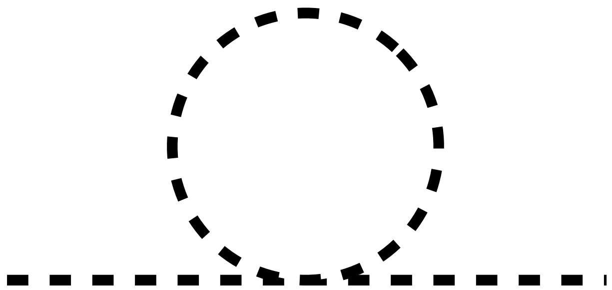
*Only a selection of the available mass limits on new states or phenomena shown

The state of SUSY @Planck2012



What counts for supersymmetric naturalness?

Corrections to the Higgs (soft) mass are driven by the top/stop system, since the top yukawa is so large



$$\Delta m_{H_u}^2 \sim -12 \frac{y_t^2}{16\pi^2} m_{\tilde{t}}^2 \log \frac{\Lambda_{UV}}{\mu_{IR}}$$

But there is a close relation between the scale of EWSB and the Higgs soft mass

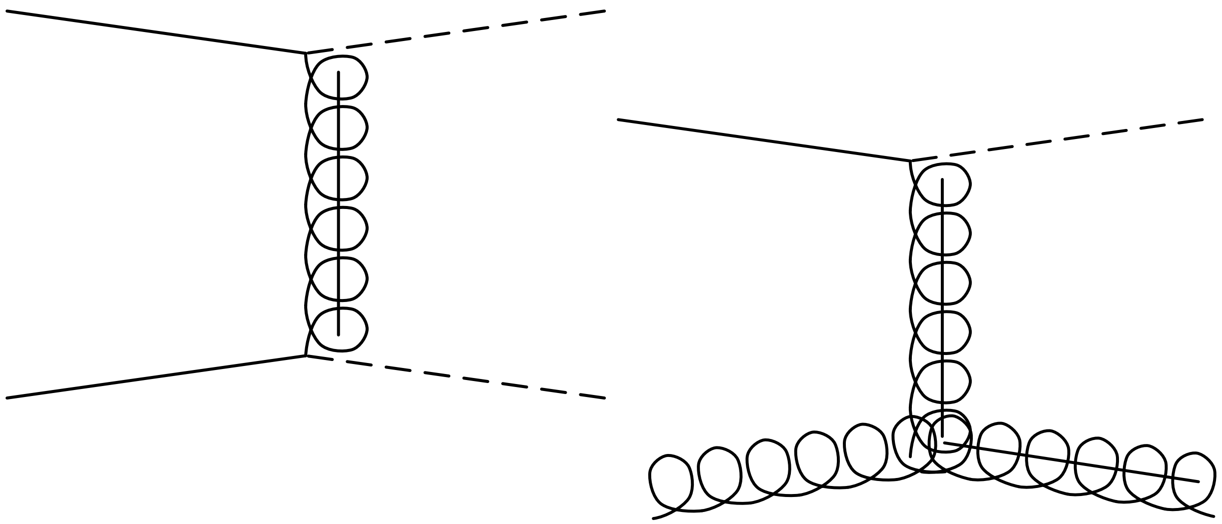
$$\frac{1}{2} m_Z^2 \simeq -\mu^2 - m_{H_u}^2$$

Stop should not be heavier than ~ few hundred GeV if SUSY is a natural solution to the hierarchy problem

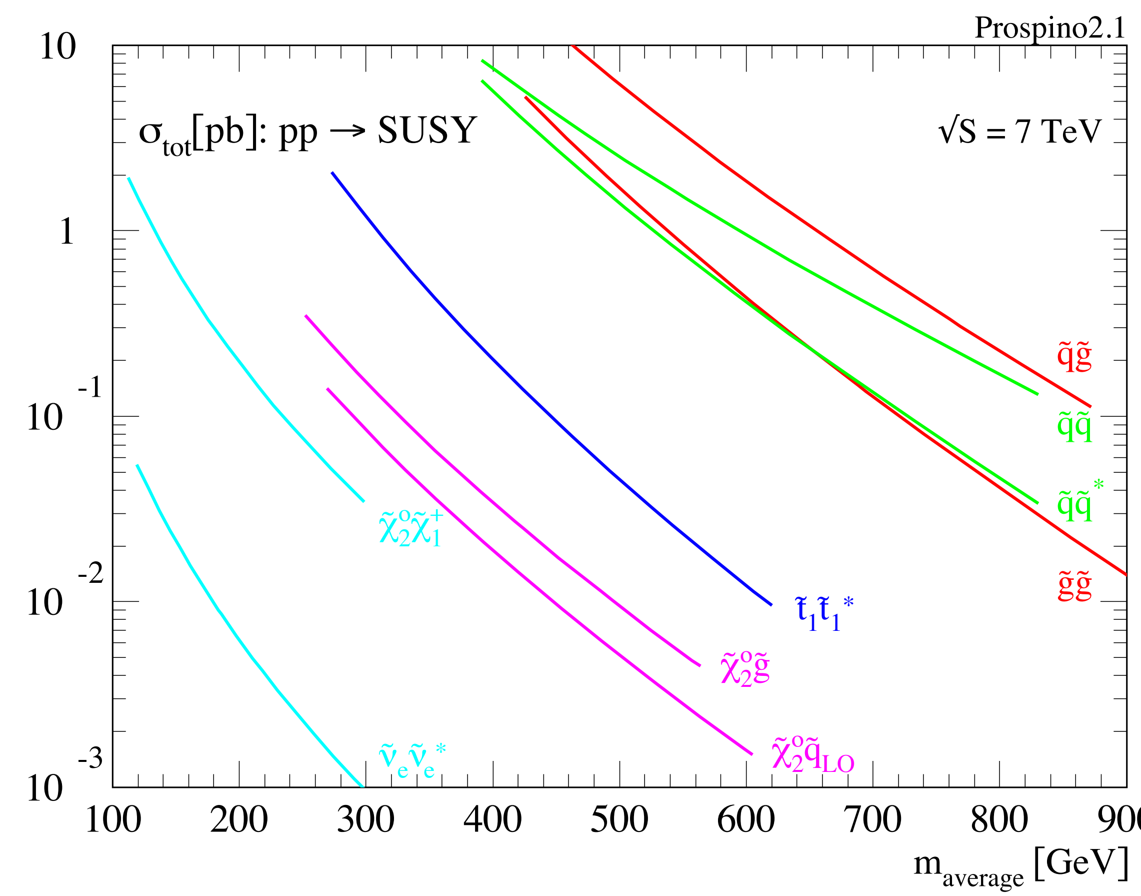
"The Alamo for SUSY naturalness" is $m_{\tilde{t}} \lesssim 1 \text{ TeV}$

What's behind current LHC SUSY limits?

Current limits are driven by squark pair production and squark-gluino associated production



These processes are dominated by *first-generation* squarks



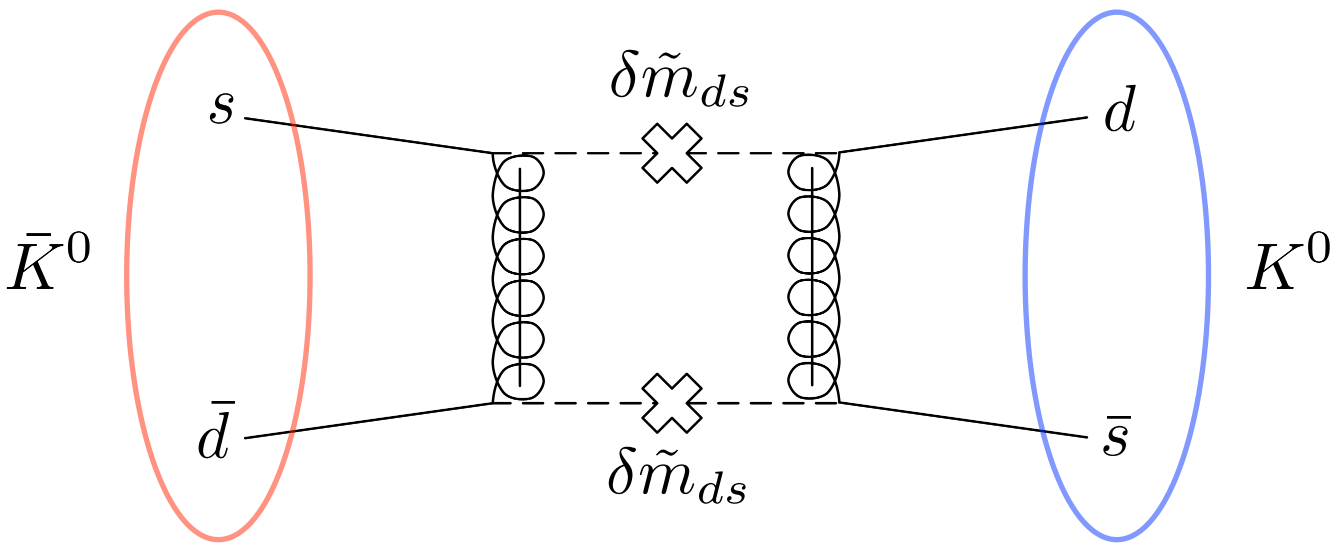
SUSY may be natural and consistent if we decouple first-generation squarks while keeping third-generation squarks light

Light stops especially hard to exclude

[Kats, Shih; Kats, Meade, Reece, Shih; Essig, Izaguirre, Kaplan, Wacker; Brust, Katz, Lawrence, Sundrum; Papucci, Ruderman, Weiler; + 3 preprints this morning]

The trouble with sflavor

A strong constraint on SUSY models; any significant mixing in the soft masses prohibited by FCNCs



$$\frac{1}{\Lambda^2}(\bar{s}_R d_L)(\bar{s}_L d_R)$$

$$\Lambda \gtrsim 2 \times 10^4 \text{ TeV (no CPV)}$$

$$\Lambda \gtrsim 3 \times 10^5 \text{ TeV (O(1) CPV)}$$

Even with Cabibbo alignment, sfermions above 50 TeV!

So SUSY breaking needs to know enough about flavor to distinguish the stops, but not enough to distinguish first 2 gens.

(Favors U(2) flavor symmetry -- c.f. Barbieri's talk)

A model-builder’s challenge

- Enormous attention being devoted to natural SUSY spectra; would be great to have models, perhaps extra predictions & observables. *There are lots of simplified searches being done; would like to motivate topologies.*

- Need light stops, heavy first two generations...

- ...but also U(2) sflavor symmetry. Could always do this by hand, but so much nicer if it ties directly into flavor.

- And gluinos can’t be too heavy (or the cutoff must be very low).

- Compositeness is an appealing route, but it would be a shame to lose the successful prediction for unification.

- ...and then there’s the Higgs mass.

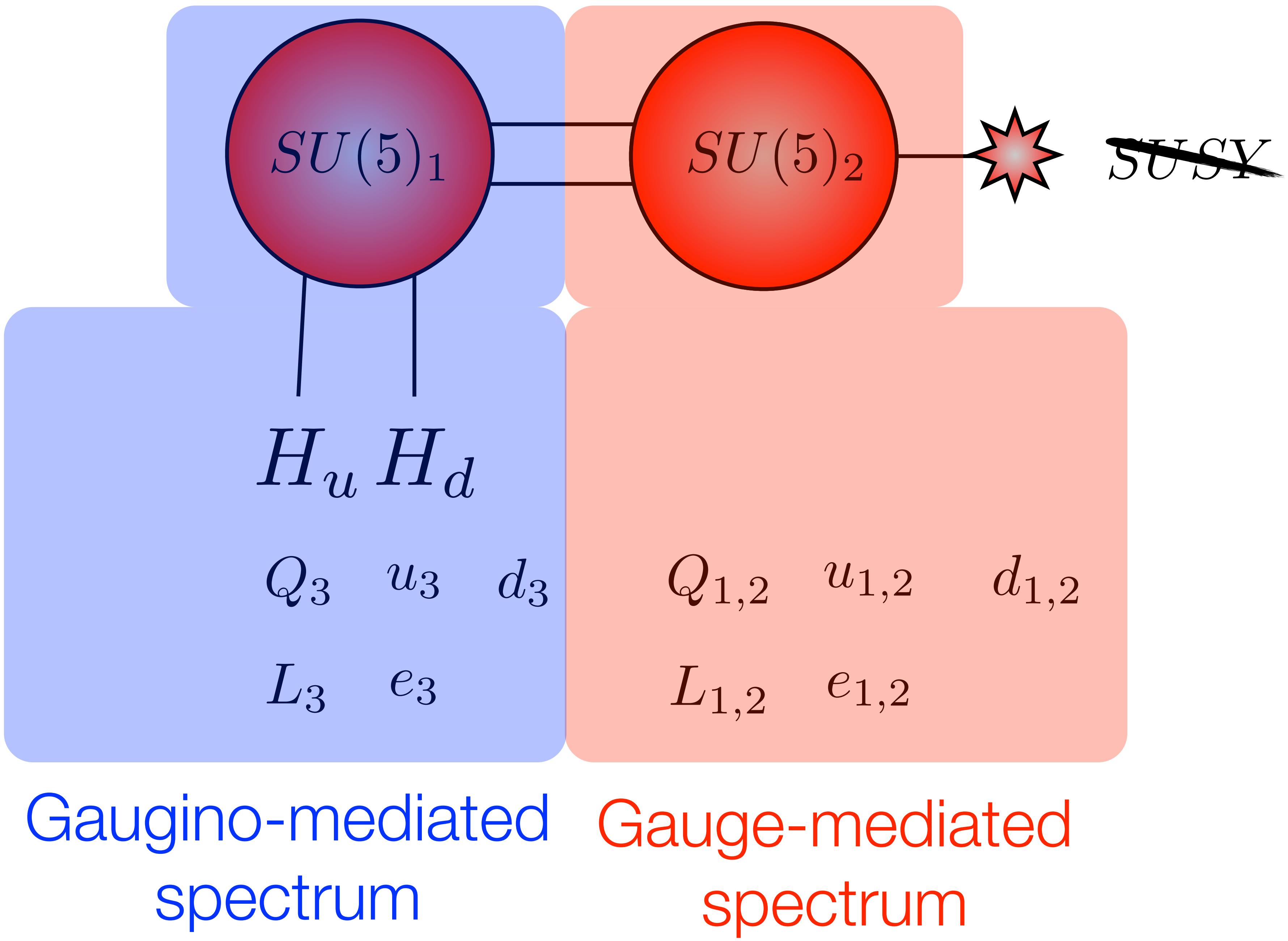
A model-builder's dichotomy

UV Models	IR Models
New physics decoupled in energy	New physics right above our heads
New d.o.f. weakly constrained by flavor, PEWK, etc.	New d.o.f. tightly constrained by flavor, PEWK, etc.
Harder to discover/falsify	Easier to discover/falsify
Look for natural SUSY spectrum, flavor observables @LHC	Look for natural SUSY spectrum, flavor observables, additional states, Higgs properties @LHC
No real explanation for Higgs mass	Potential explanation for Higgs mass

An IR Model: “Split families”

- One radical possibility is to imagine that SM families are not all charged under the same gauge symmetry in the UV
- This gives a theory of flavor because not all Yukawa couplings are allowed by gauge invariance
- If SUSY breaking occurs at low scales via gauge mediation, this also gives a related theory of sflavor
- Must break to the SM group at some scale; if this scale is low, the Higgs mass comes out nicely
- Could also think of this picture as an effective theory for your favorite extra-dimensional model

Splitting the families



Link field vev breaks gauge groups to diagonal

$$\langle \chi \rangle : \quad G_{SM}^{(1)} \times G_{SM}^{(2)} \to SU(3)_c \times SU(2)_L \times U(1)_Y$$

A U(2) symmetric model of flavor

Gives a model of SM flavor from gauge invariance:

Yukawa couplings suppressed by powers of $\epsilon \equiv \frac{\langle \chi \rangle}{M_*}$

(a sort of "nonabelian" Froggatt-Nielsen)

E.g., $$\Delta W \sim \frac{H_u \tilde{\chi}_l Q_2 \bar{u}_2}{M_*} + \frac{H_d \chi_l Q_2 \bar{d}_2}{M_*}$$

$$Y_u \sim \sin\beta \begin{pmatrix} \epsilon & \epsilon & 0 \\ \epsilon & \epsilon & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad Y_d \sim \cos\beta \begin{pmatrix} \epsilon & \epsilon & 0 \\ \epsilon & \epsilon & 0 \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

[see also Barbieri et al.1105.2296]

Flavor predictions

Fermion masses

$$m_{u,c} \propto \sin\beta\, \epsilon\, v \qquad m_t \propto \sin\beta\, v$$

$$m_{d,s} \propto \cos\beta\, \epsilon\, v \qquad m_b \propto \cos\beta\, v$$

CKM matrix

$$V_{CKM} \sim \begin{pmatrix} 1 & 1 & \epsilon^2 \\ 1 & 1 & \epsilon^2 \\ \epsilon^2 & \epsilon^2 & 1 \end{pmatrix}$$

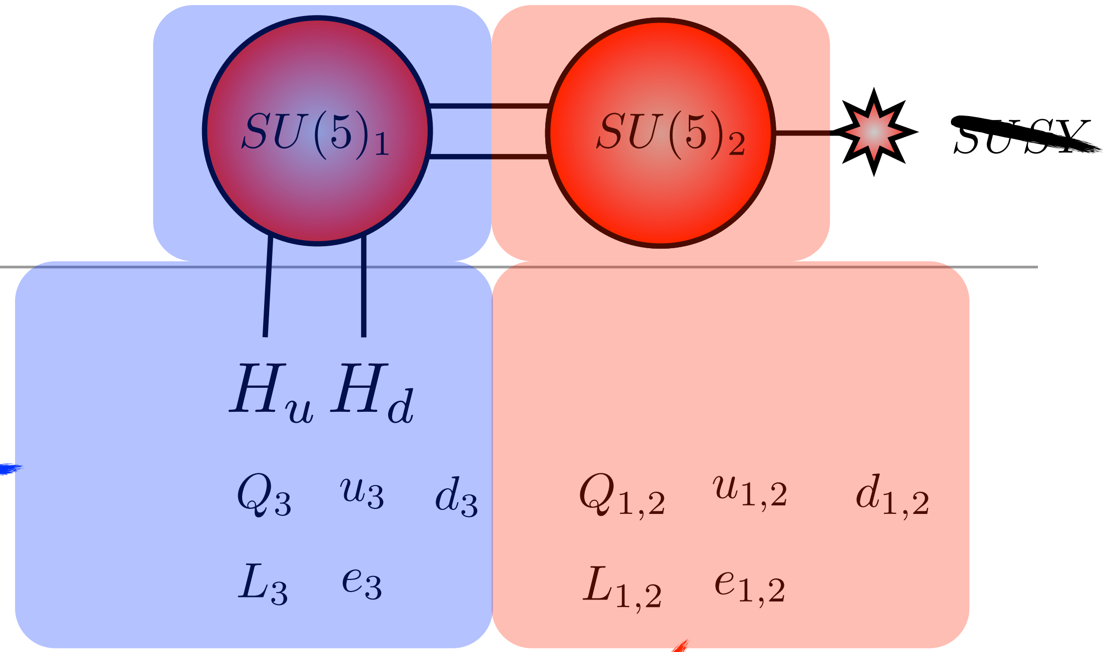
(Two gauge groups means only two hierarchies, two small CKM angles)

(Easy enough to build a 3-site model, but FCNCs constraining)

$$\epsilon \sim \frac{m_c}{m_t} \sim \frac{m_s}{m_b} \longrightarrow \epsilon \sim \mathcal{O}\left(10^{-2}\right)$$

NB: Generating the necessary flavor operators requires a $\mathbf{5} + \bar{\mathbf{5}}$ under G_1 and a vector-like doublet pair under G_2

SUSY spectrum



$$m^2_{\tilde{g}M} \sim \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{v}{M}\right)^2 \left(\frac{F}{M}\right)^2$$

$$m^2_{GM} \sim \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$

Precise spectrum depends on whether or not gaugino masses are suppressed in F/M

Unsuppressed $\longrightarrow$ Moderate deviations from gauge mediation

Suppressed $\longrightarrow$ 1st & 2nd gen scalars heavy and decouple

How much do we split the spectrum?

A variety of effects connect soft masses between the two sites at one loop, so that

$$\tilde{m}_1 \simeq \frac{1}{4\pi} \tilde{m}_2$$

Also cuts off radiative corrections from gluinos!

Also can give a token solution to the mu problem:

$$W \sim \frac{\chi \tilde{\chi} H_u H_d}{M_*} \longrightarrow \mu_{eff} \sim \frac{v^2}{M_*}$$

Correct predictions for μ, flavor hierarchy require

$$\langle \chi_l \rangle \lesssim 10 \ \mathrm{TeV}, \qquad M_* \lesssim 10^3 \ \mathrm{TeV}$$

Natural scales if $M_* \sim M_{\mathrm{mess}}$ (low-scale gauge mediation)

Sflavor?

Despite being flavorful SUSY breaking, triply protected against prohibitive FCNCs

Soft masses diagonal in gauge eigenbasis;
in fermion mass eigenbasis they are rotated to

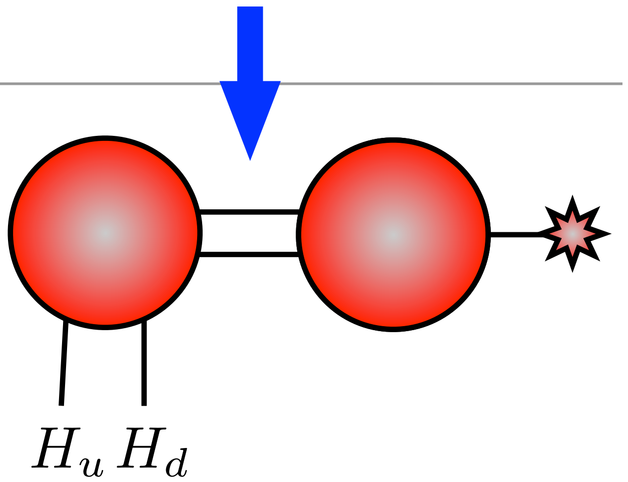
$$m_{\tilde{Q}}^2 \sim \begin{pmatrix} m_{GM}^2 & 0 & \epsilon^2 m_{GM}^2 \\ 0 & m_{GM}^2 & \epsilon^2 m_{GM}^2 \\ \epsilon^2 m_{GM}^2 & \epsilon^2 m_{GM}^2 & m_{\tilde{g}M}^2 \end{pmatrix}$$

U(2) symmetry in first two generations

Combined alignment + decoupling sufficient for remaining FCNCs; largest contribution (though safe) is to B-B mixing

...and the Higgs mass

Non-supersymmetric, non-decoupling D-term from heavy scalars:



$$\delta V = \frac{g^2\Delta}{8}\left|H_u^\dagger\sigma^a H_u - H_d\sigma^a H_d^\dagger\right|^2 + \frac{g'^2\Delta'}{8}\left|H_u^\dagger H_u - H_d H_d^\dagger\right|^2$$

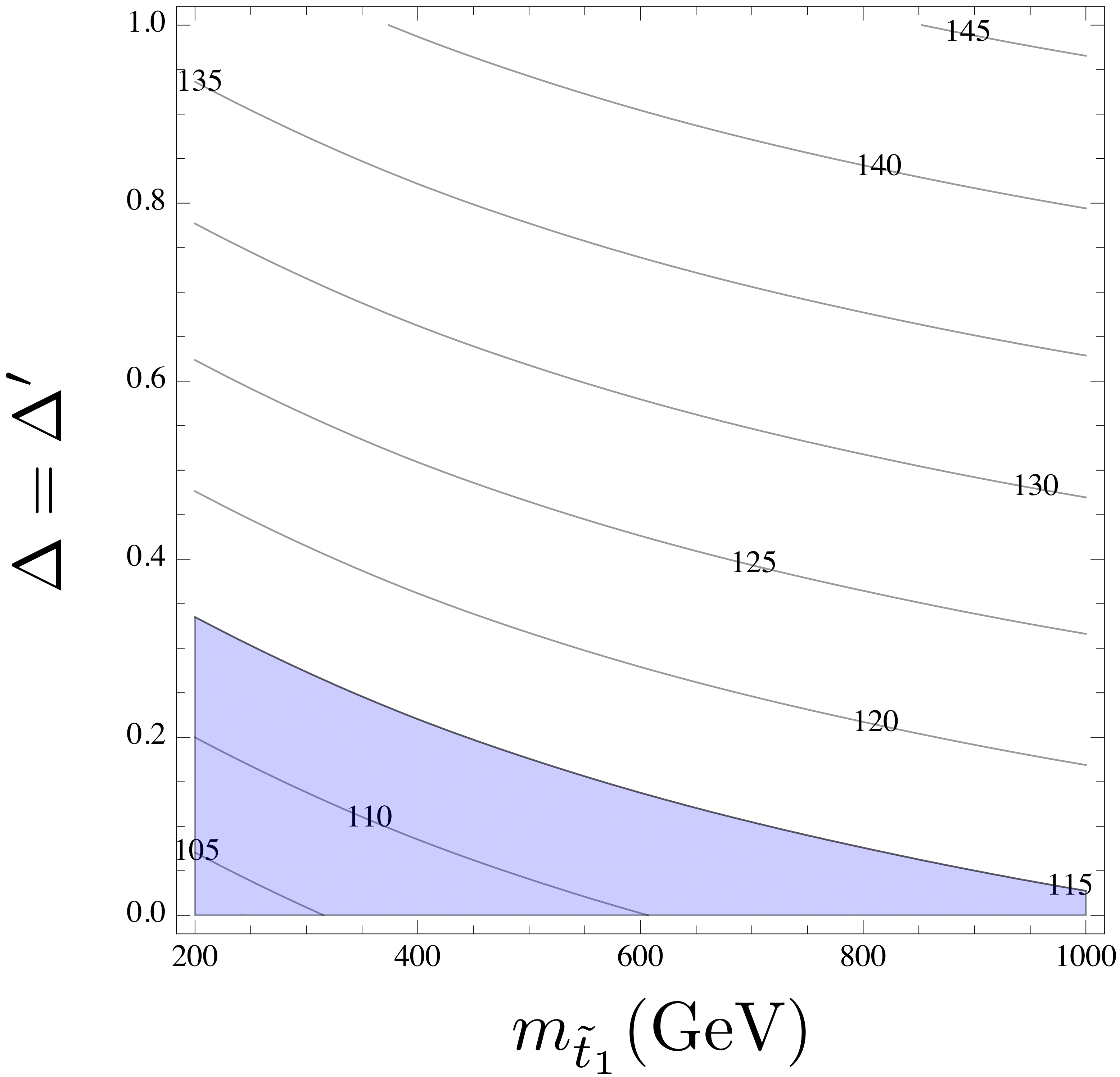
where $$\Delta = \frac{g_1^2}{g_2^2}\frac{2\tilde{m}_\chi^2}{M^2+2\tilde{m}_\chi^2}$$

Shifts tree-level bound on Higgs mass $$m_h^2 \lesssim m_Z^2 + \frac{g^2\Delta + g'^2\Delta'}{2}v^2$$

Corrections can easily shift tree-level Higgs mass 10-20 GeV

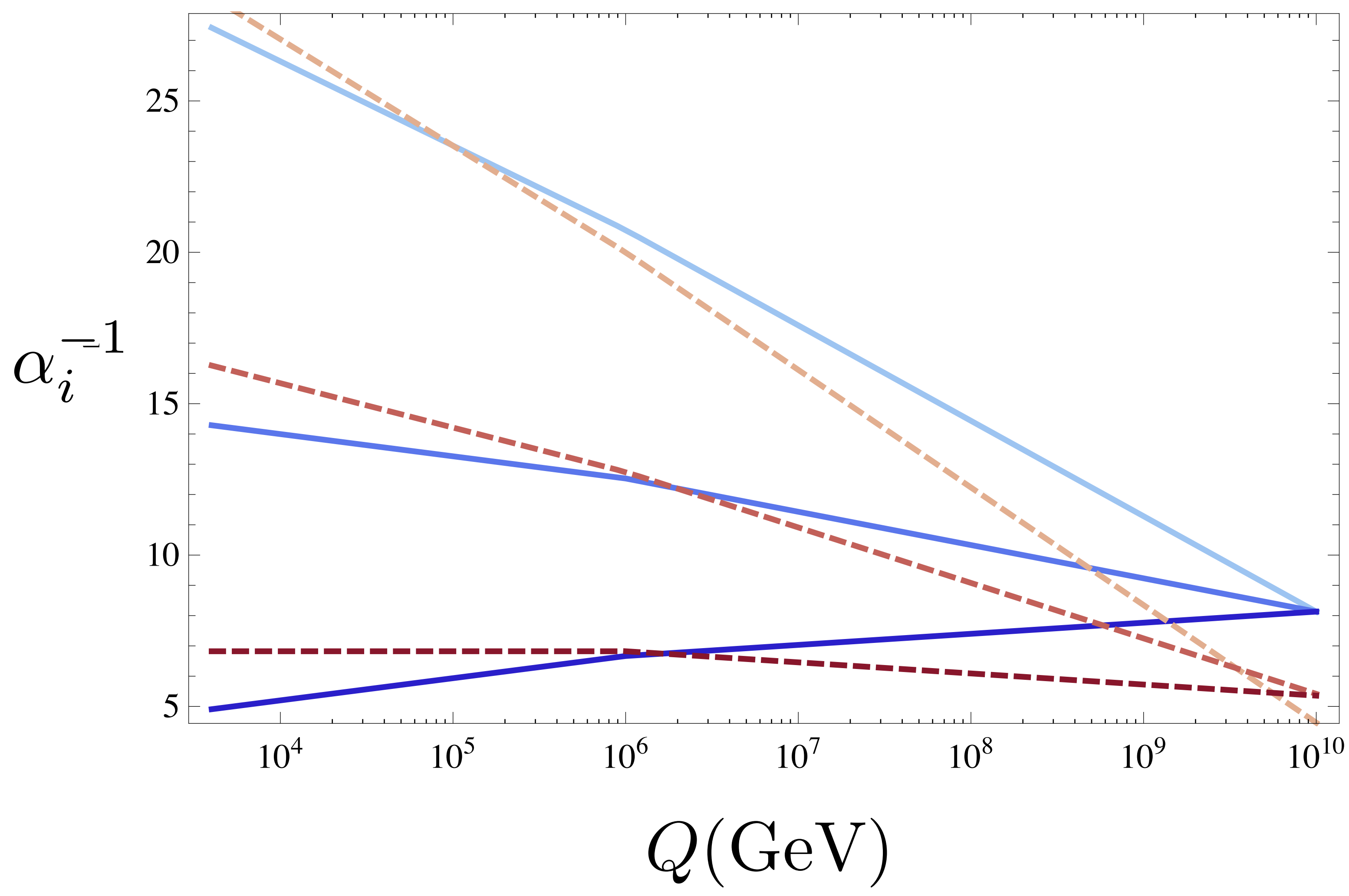
The Higgs mass with quartic correction

[Higgs mass with 2-loop radiative corrections in FeynHiggs + tree-level quartic correction]



Unification?

Might be concerned that this picture wholly surrenders unification.



In fact, the most natural picture involves unification on both sides; *both* gauge groups have unified multiplets plus extra SU(2) matter.

Split family values

- Broad features of SM flavor arise from dividing gauge group in the UV
- Stops are light, 1st- and 2nd-gen squarks heavy; compatible with LHC limits
- Soft masses arise from gauge & gaugino mediation
- Flavorful soft spectrum, free of problematic FCNCs
- D-term corrections lift the tree-level Higgs mass easily to 125 GeV
- Unification prediction preserved
- Extra states from higgsing might lie in far LHC reach

[NC, McCullough, Thaler 1201.2179, 1203.1662]

A UV Model: “Flavor mediation”

- One way to relate sflavor and flavor is by communicating SUSY breaking through a (gauged) Standard Model flavor symmetry.
- Gauged SM flavor symmetries must be spontaneously broken to generate SM flavor. So spectrum is one of *Higgsed gauge mediation.*
- Higgsed gauge mediation translates a hierarchy in gauge boson masses into a hierarchy in soft masses
- This communicates SM flavor to the sflavor spectrum in a direct and predictive fashion. *And has some surprising features...*

First, some Higgsed gauge mediation

Would like to compute the soft masses that result from gauge mediation via a spontaneously broken gauge group

Take minimal GMSB....

$$\boldsymbol{W} = \boldsymbol{X}\boldsymbol{\Phi}\boldsymbol{\Phi}^{\boldsymbol{c}} \qquad \langle \boldsymbol{X} \rangle = M + \theta^2 F$$

(SUSY breaking spurion connected to messengers)

...but now the vector fields also have a supersymmetric mass

$$M_V^2$$

Expect deviations from mGMSB as a function of mass scales

Soft masses in higgsed GM

To leading order in *F/M* and all orders in M_V/M:

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

in gauge boson mass eigenbasis $\quad {M_V^a}^2 = \left[{D_V}^2\right]^{aa}$

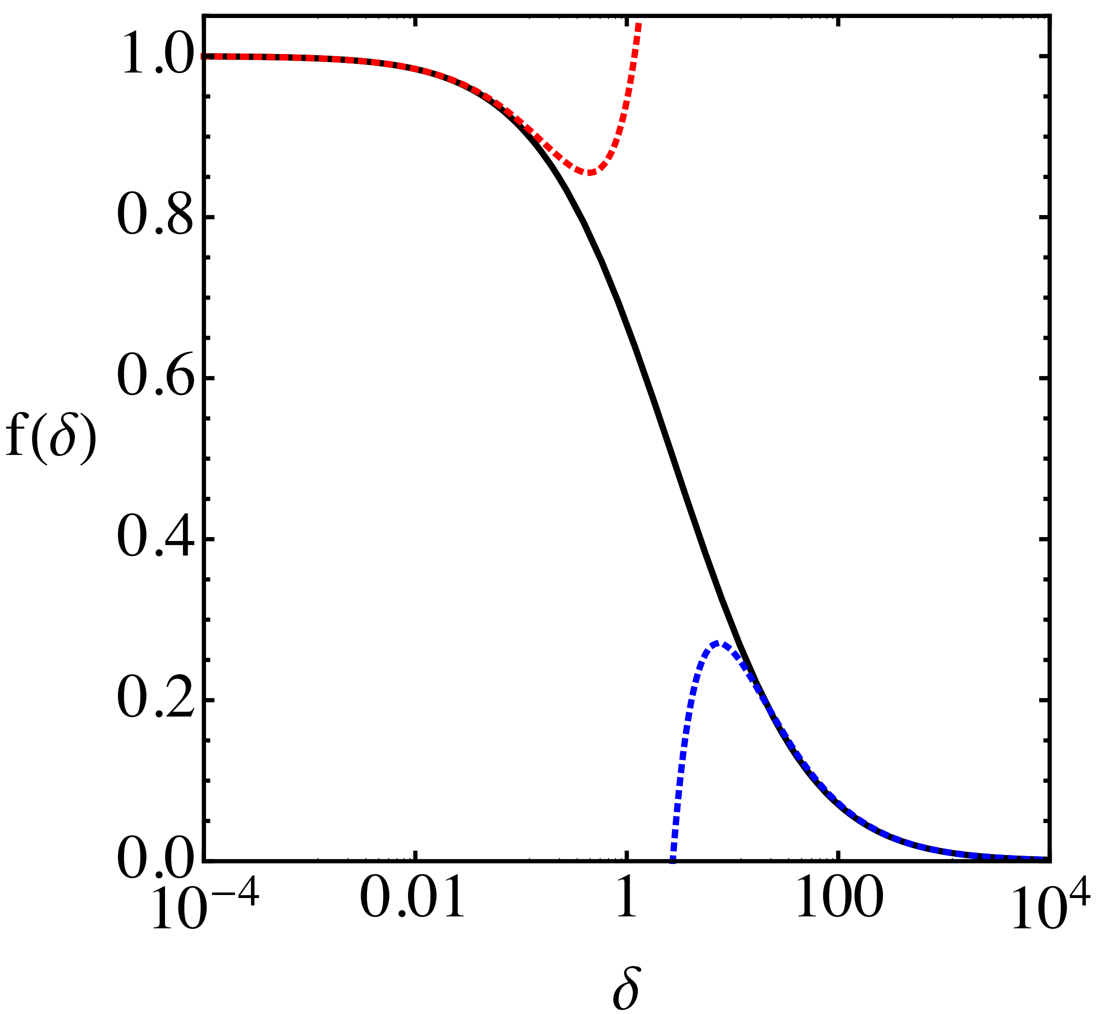
where the physics of Higgsing is contained in the function

$$f(\delta) = 2\,\frac{\delta(4-\delta)((4-\delta)+(\delta+2)\log(\delta)) + 2(\delta-1)\Omega(\delta)}{\delta(4-\delta)^3}$$

Asymptotics of higgsed GM

Asymptotic behavior is what you'd expect:

$$\lim_{\delta\to\infty} f(\delta) = 2\frac{\log(\delta)-1}{\delta} \qquad \lim_{\delta\to 0} f(\delta) = 1 + \frac{\delta}{3}\left(\log(\delta) - \frac{1}{6}\right)$$



As the gauge masses are taken large, the soft masses vanish; as they are taken small, the usual GMSB result is restored.

Particularly interesting when the separation of scales is O(100) or more; an order-of-magnitude suppression in soft masses.

From higgsed GM to flavor mediation

- Gauge bosons with masses at or near the messenger scale have a significant impact on the soft spectrum.
- Can lead to a significant suppression of soft masses as the gauge boson mass is increased relative to the messenger scale.
- Most importantly, the soft masses are a rapidly-changing function of this ratio!
- Makes clear the heuristic idea of flavor mediation: the massive gauge bosons associated with spontaneously breaking a flavor symmetry will have a mass hierarchy coming from the hierarchy in Yukawa couplings
- This gauge hierarchy will then be translated directly to a generational hierarchy in soft masses!

Gauging a flavor symmetry

Now we want to imagine a SM flavor symmetry is gauged at high energies.

What is the simplest gauged 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

[Berezhiani; King & Ross]

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

Compatible with grand unification, since all fields treated equally

NB: $U(3)_F$ anomalous; added $U(1)$ is a killer

Breaking a flavor symmetry

Yukawas transform as $\bar{3} \times \bar{3}$

Could generate with multiple fundamentals or a rank-2 tensor

Generate SM Yukawas with two symmetric tensors S_u, S_d

(Gives the maximal hierarchy in flavor gauge boson masses)

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

Up to flavor rotations, break the flavor symmetry via

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

Must assume these vevs are nearly or completely D-flat.

Gauge bosons of the broken flavor symmetry

There is some parametric freedom;
SM flavor hierarchy is fixed up to one free parameter

$$\frac{m_t}{m_b} = \frac{v_{u3}}{v_{d3}}\alpha, \qquad \alpha \equiv \frac{M_{S_d}}{M_{S_u}} \tan\beta$$

For simplicity let's focus on $\alpha = 1$

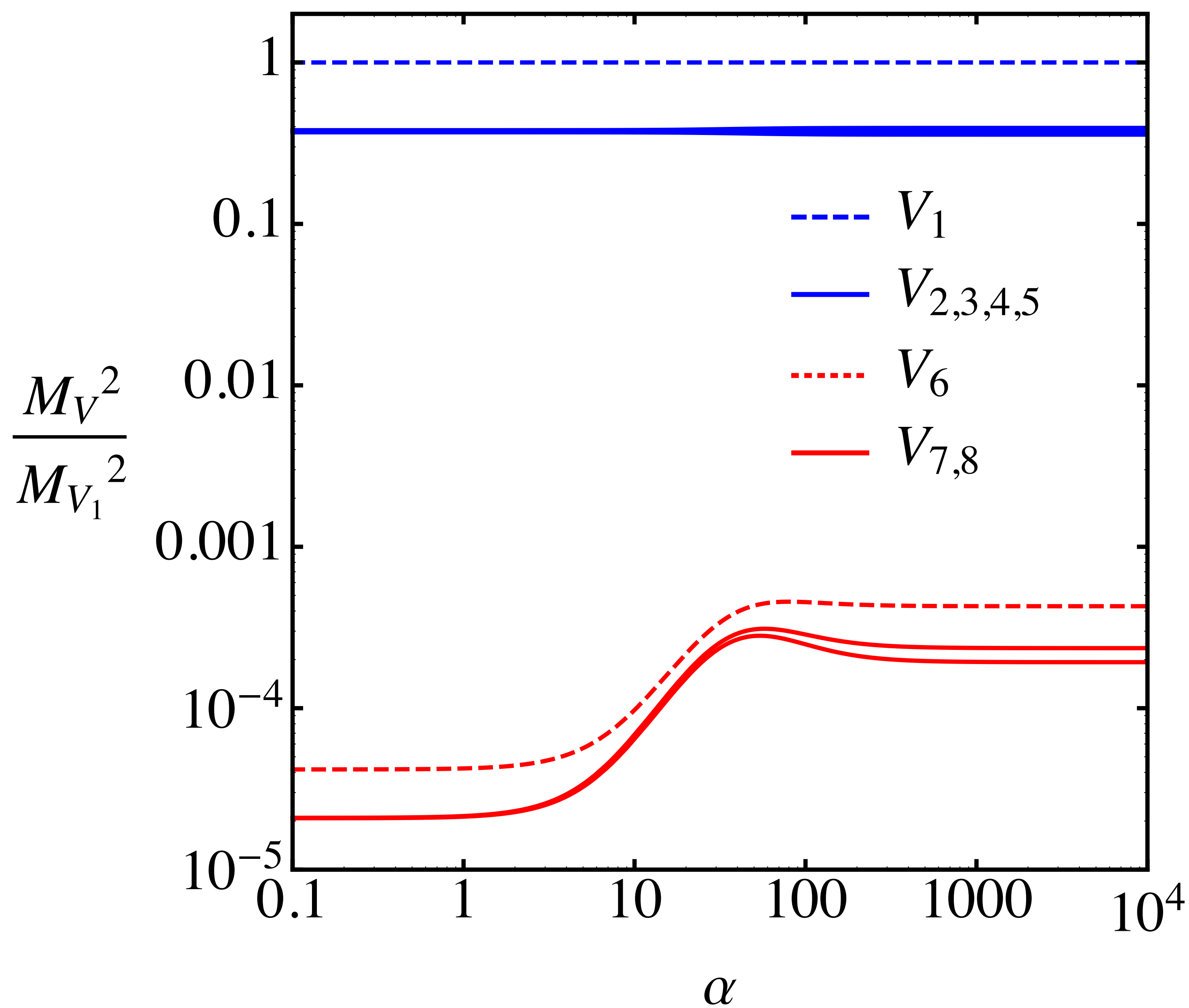
though anything up to $\alpha \lesssim 100$ is viable.

Then to leading order, the gauge boson masses are

$$M_V^2 = g_F^2 \left\{ \frac{8}{3} v_{u3}^2, (v_{u3} + v_{u2})^2, v_{u3}^2, v_{u3}^2, (v_{u3} - v_{u2})^2, 2v_{u2}^2, v_{u2}^2, v_{u2}^2 \right\}$$

The magic of SU(3)

Spectrum of gauge bosons normalized to most massive:



Breaking pattern is approximately

$$\mathrm{SU}(3)_F \to \mathrm{SU}(2)_F$$

followed by

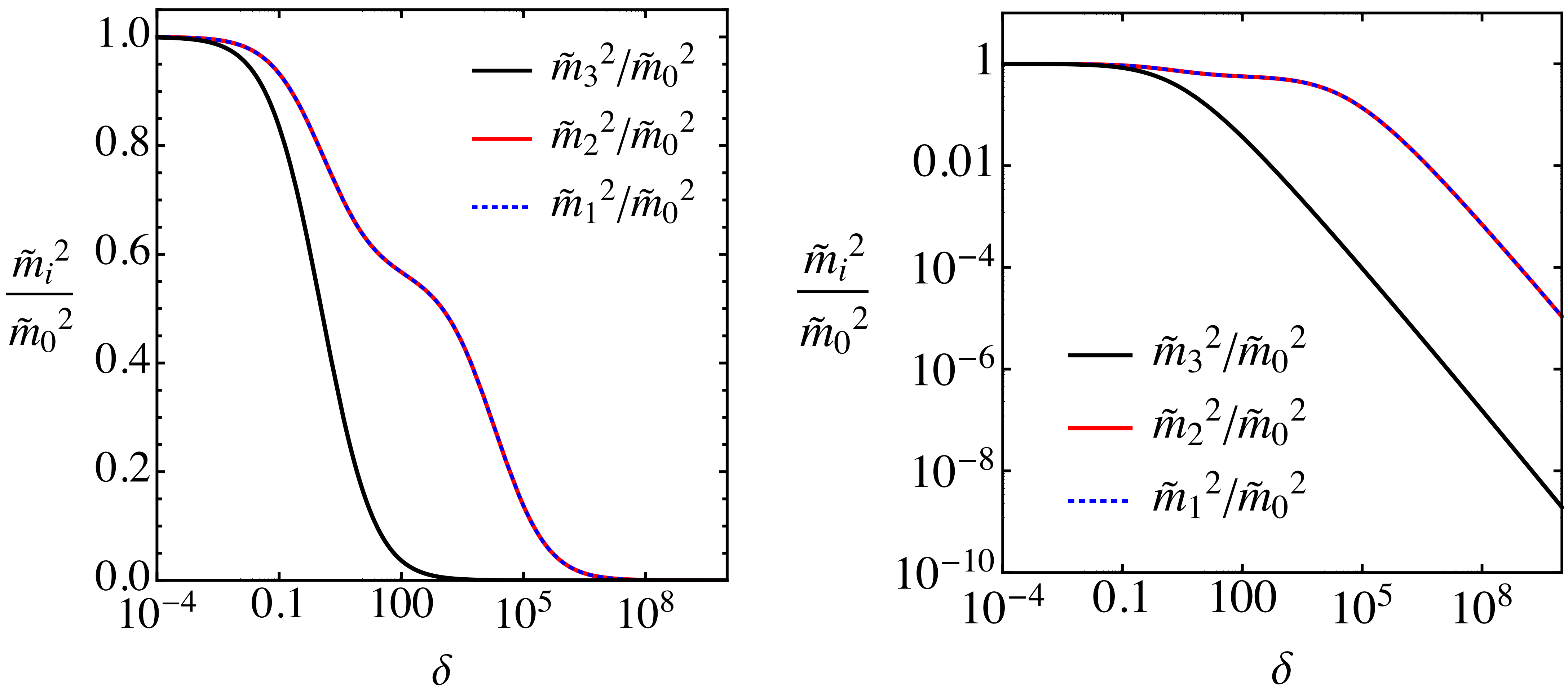
$$\mathrm{SU}(2)_F \to \emptyset$$

The key feature: SU(3) is rank-2

Soft masses in flavor mediation

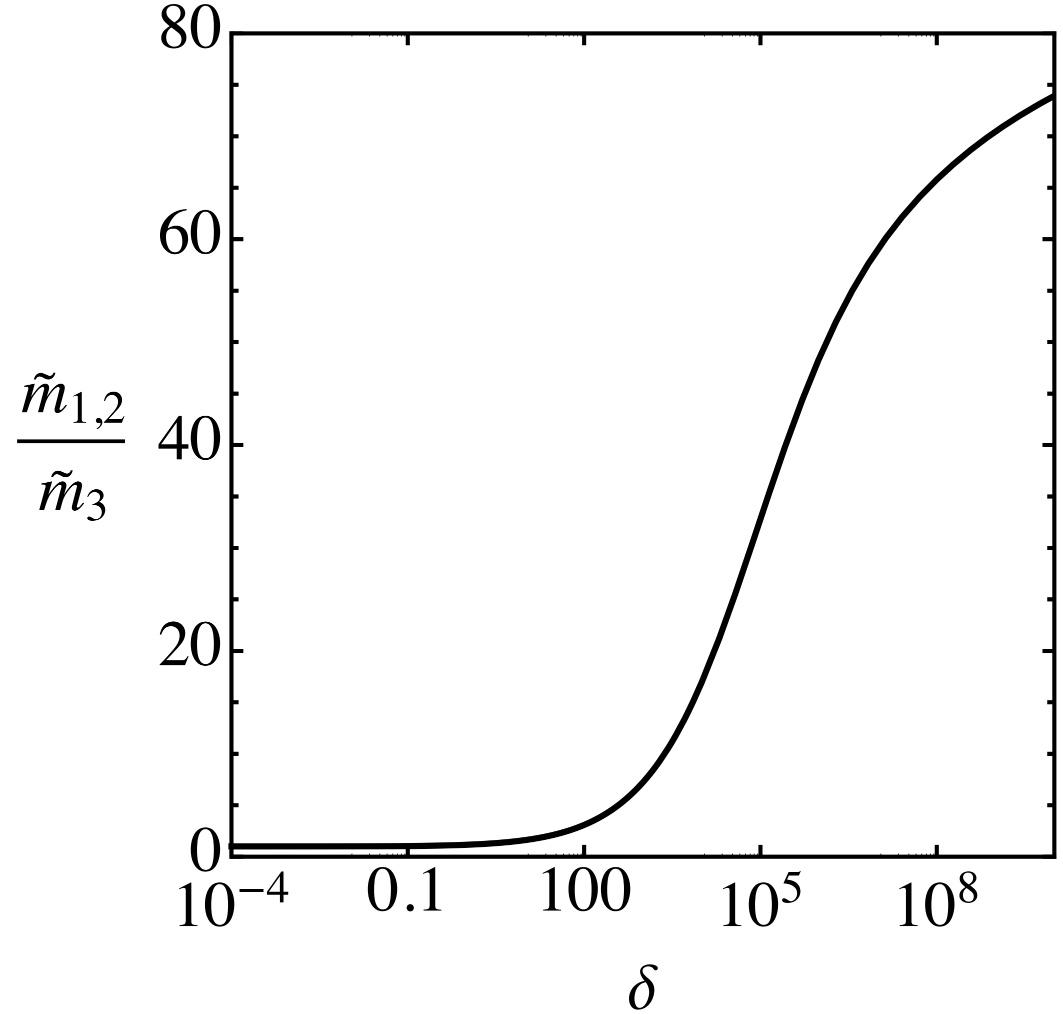
This pattern of Higgsing feeds into soft masses via

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

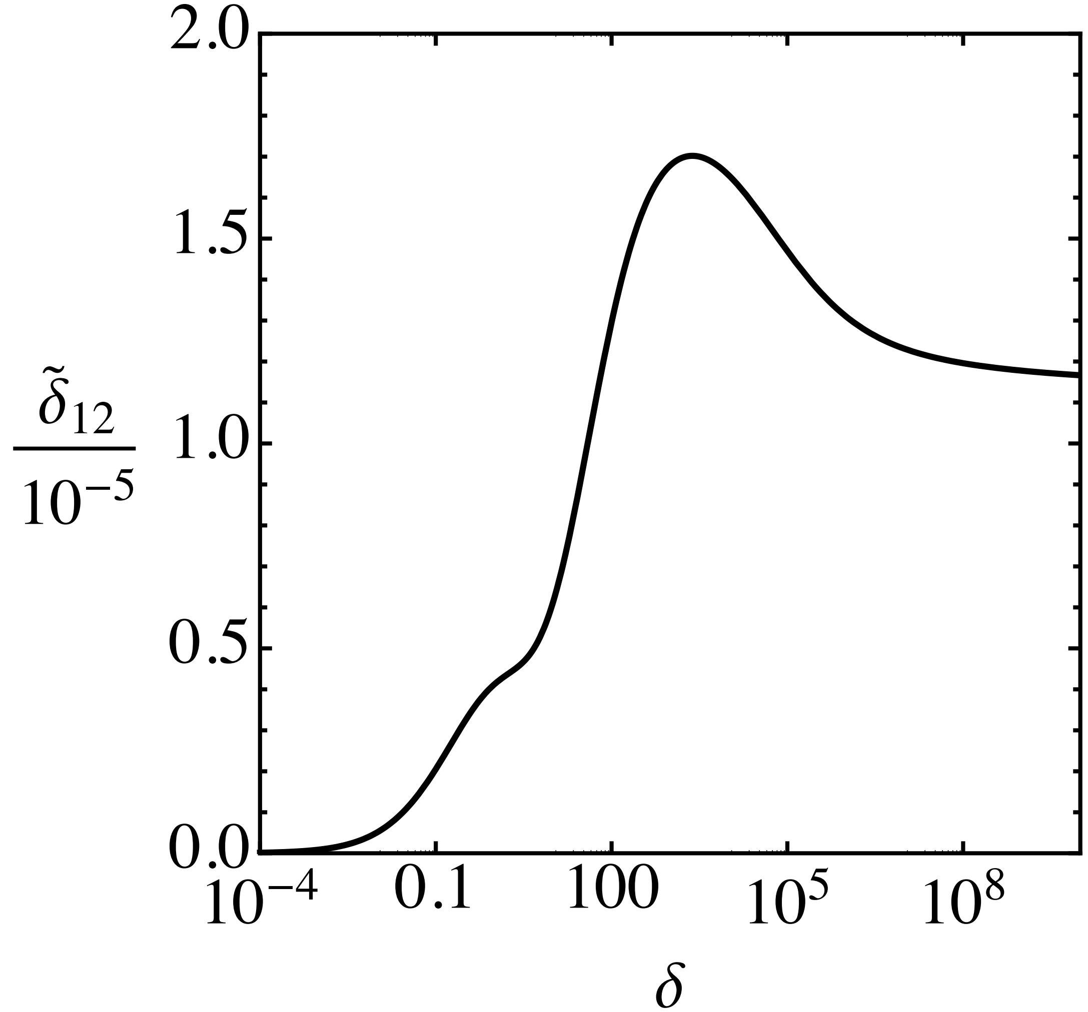


There is a *U(2)* sflavor symmetry from *SU(3)* > *SU(2)* > nothing !!

How well do we do?



Hierarchy



U(2) symmetry

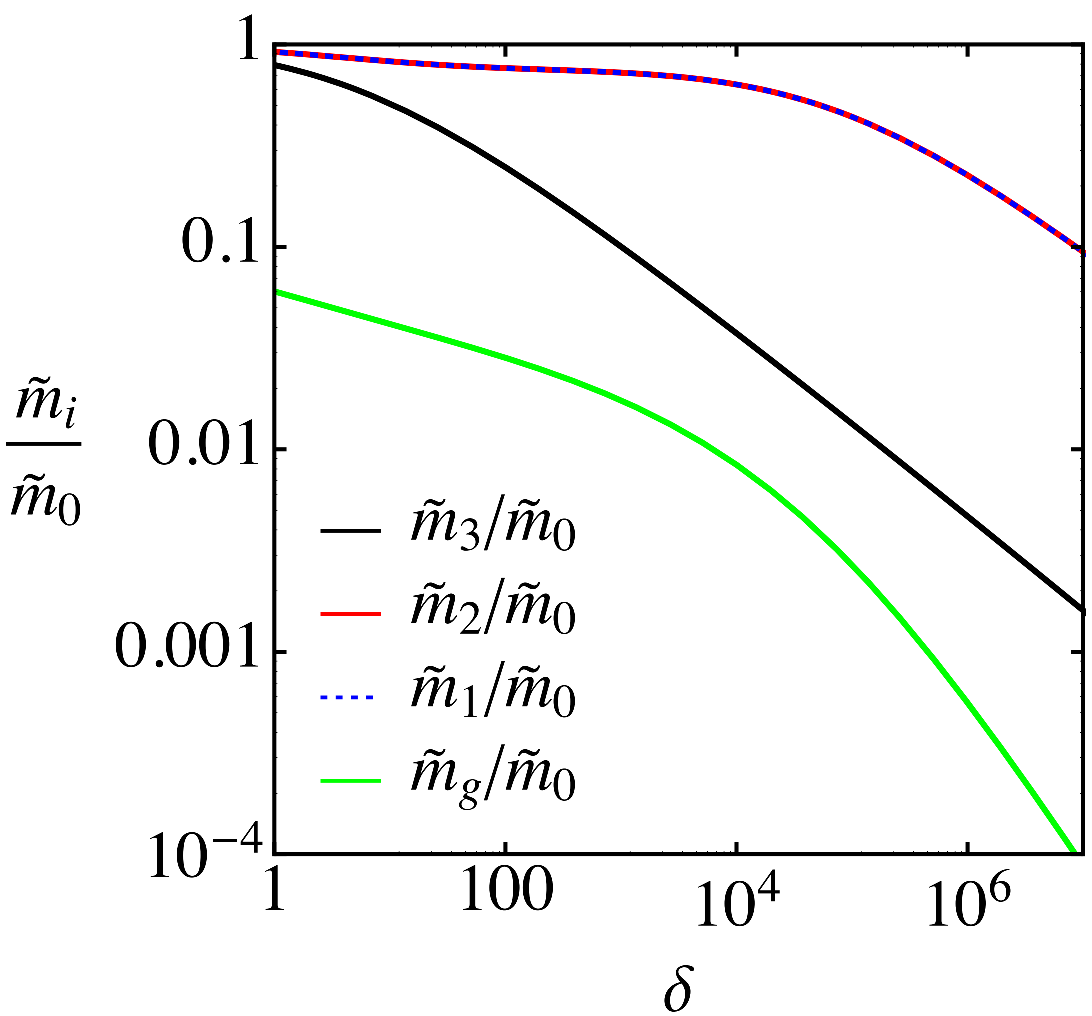
These features are not unique to our specific choice of symmetry breaking.
The key is that the flavor symmetry is strongly broken in the third generation.

What about the...

Gauginos of the SM gauge group?*

We communicated SUSY breaking via gauge mediation, but not of SM group; at leading order the MSSM gauginos are massless.

Native source of gaugino mass comes in at three loops feeding off flavor gaugino mass



Even maximizing the possible contributions, in a perturbative setting the gluino mass from these three-loop diagrams comes out too small (< 500 GeV)

Suggests we generally need another source of SUSY breaking

*The Higgses also need soft masses, but this is a feature.

A complete model

Need an additional source of SM gaugino masses. Many possibilities: gauge mediation, gaugino mediation, gravity mediation, etc.

(Can have a high messenger scale due to the gauged flavor symmetry)

Perhaps the most natural candidate is to treat all gauge groups on equal footing, and consider gauge mediation via both SM and flavor gauge groups.

Can get a viable spectrum from a single messenger scale.

Also need an origin for EWSB parameters and the Higgs mass. No intrinsic explanation, but see e.g. David Shih's talk on Thursday

Three simple examples...

- Semi-democratic: SM + flavor messengers, M_V ~100 M, order of magnitude splitting between 1/2 and 3 generation, need flavor gauge coupling very large or tuned coupling to messengers.

- Democratic: SM + flavor messengers, M_V ~ M, factor of ~few splitting between 1/2 and 3 generation, flavor gauge coupling same order as SM couplings, no tuned couplings.

- Mini-split: Just flavor messengers. MSSM gaugino masses and Higgs soft masses at three loops; stop must be ~few TeV to bring up gluino mass above limits. 1/2 generation above 10 TeV.

- <Insert your favorite idea here>

The flavor of Flavor Mediation

- Mediating SUSY breaking through a gauged flavor symmetry naturally correlates light third-generation sfermions with heavy third-generation fermions through Higgsed gauge mediation.

- For the simple anomaly-free choice of $SU(3)_F$, a U(2) sflavor symmetry arises automatically because SU(3) is rank 2.

- FCNCs are all safely within experimental bounds, though new physics in B mesons should be just around the corner.

- No solution for the Higgs mass, but EWSB is a mess in gauge mediation anyway; need some new degrees of freedom.

- Conventional gauge coupling unification preserved.

Conclusions

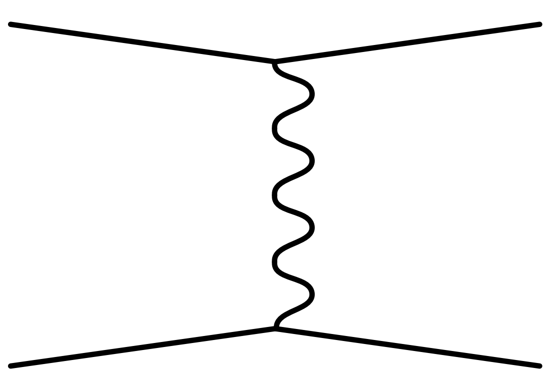
- The first year of LHC data has seriously imperiled light SUSY with universal masses; this paradigm is beginning to look either unnatural or incorrect.
- One route to rescuing SUSY naturalness arises if the third generation is significantly lighter than the first two, *provided an approximate sflavor symmetry protects against FCNC.*
- Can do this in the UV or the IR, with varying implications for phenomenology. I've discussed two simple examples, but there are infinitely many possible variations and alternatives. And many possible observables!
- Perhaps Nature is encouraging us to think unconventionally about SUSY breaking and mediation...
- ...in which case 2012 could be a very interesting year for the LHC.

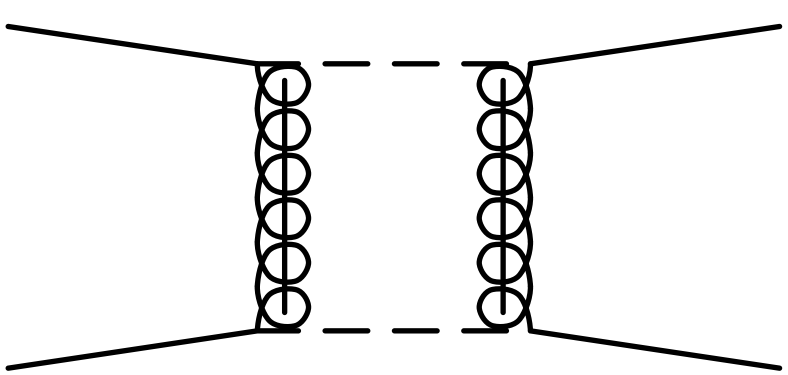
Thank you!

Extra slides

Tree-level FCNC's in flavor mediation

There are two sources of FCNCs: tree-level contributions from flavor boson exchange, plus the usual one-loop SUSY box diagrams





Tree-level: integrate out flavor bosons to obtain

$$\mathcal{L} \supset -\frac{g_F^2}{2M_{V_a}^2}(\bar{f}_M^i \gamma^\mu T_{ij}^a f_M^j)(\bar{f}_N^k \gamma_\mu T_{kl}^a f_N^l),$$

Limits on this dim-6 operator strongest from K-K mixing, corresponding to the lightest flavor bosons

$$v_{u2} \gtrsim 10^4 \text{ TeV } (1.4 \times 10^5 \text{ TeV})$$

Without (with) O(1) new CPV

No problem given the scales we're interested in.

One-loop FCNC's in flavor mediation

Strongly protected from one-loop SUSY FCNCs

U(2) sflavor symmetry plus heavy 1st, 2nd generation scalars means usual K-K mixing diagram is tiny

Most important contribution to K-K mixing is actually via the sbottom; suppressed by additional CKM matrix elements

$$\propto |V_{13}V_{23}|^2$$

Still quite safe, though O(1) new CPV is barely excluded (the usual NMFV outcome).

Most interesting constraint on scales comes from the sbottom sector, from limits on B-B mixing. Generally safe, but potentially in reach of LHCb or future b factories.