Flavor Mediation

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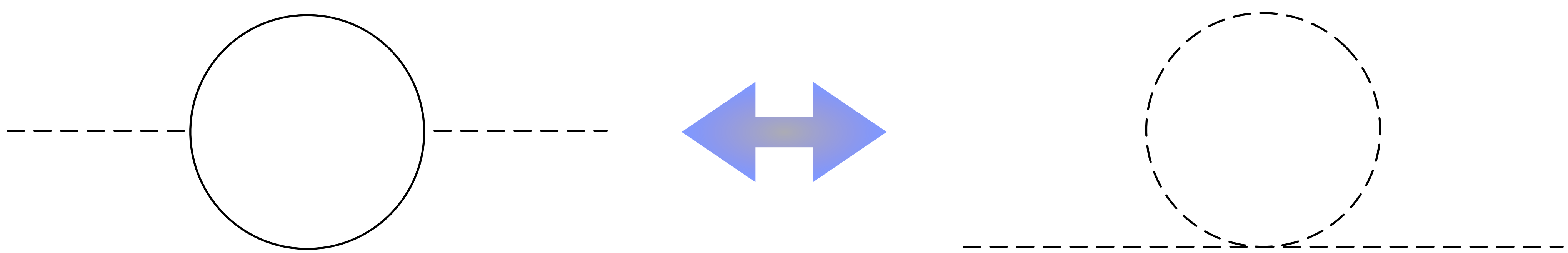
Based on work with Matthew McCullough & Jesse Thaler (MIT) *arXiv: 1201.2179 & 1203.????*

Rutgers 03.06.12

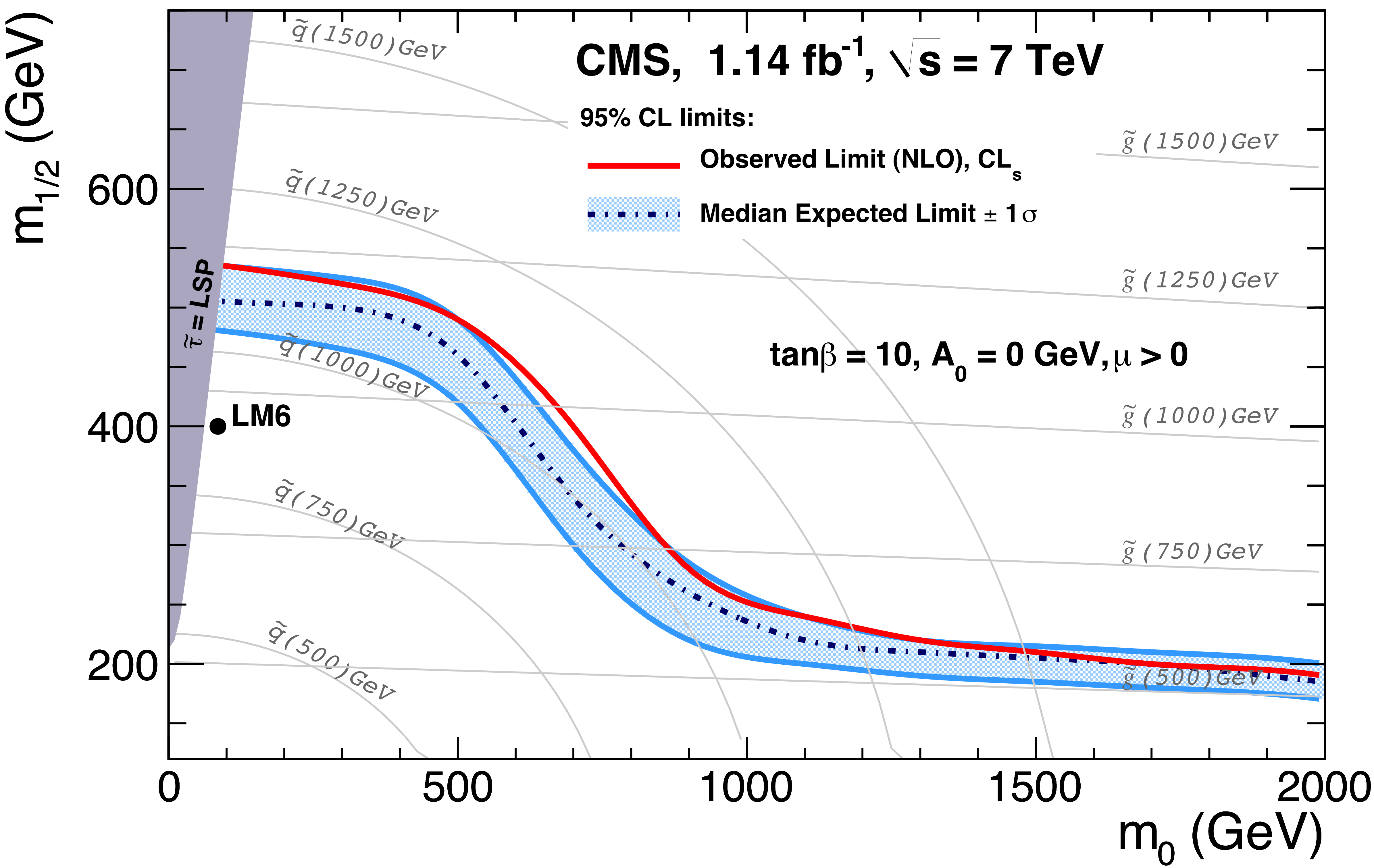
SUSY as solution to the hierarchy problem

Supersymmetry is a well-motivated solution to the hierarchy problem -- perhaps the best theoretical framework available (calculable; *most consistent with precision electroweak*)



Quadratically divergent contributions to the Higgs mass cancelled by superpartners; superpartner masses act as a cutoff for the divergences.

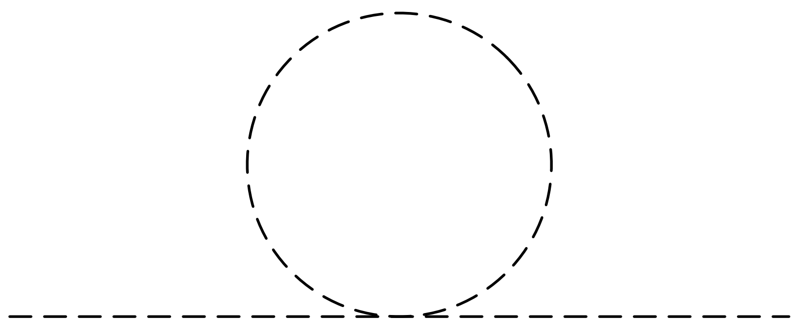
A beautiful idea, except...



[from CMS-SUS-11-003, search for SUSY w/ 2+ jets & MET]

How heavy can natural SUSY be?

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

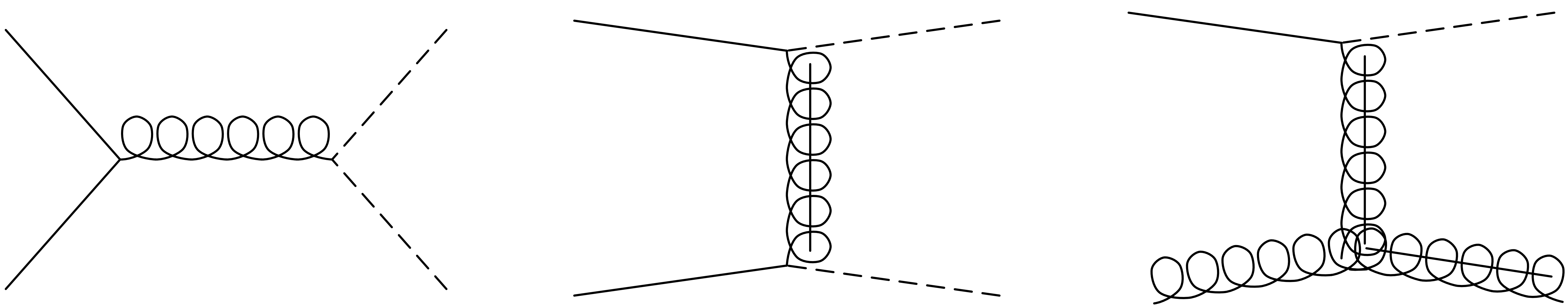
$$\frac{1}{2}m_Z^2 \simeq -\mu^2 - m_{H_u}^2$$

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

What's driving current LHC SUSY limits?

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

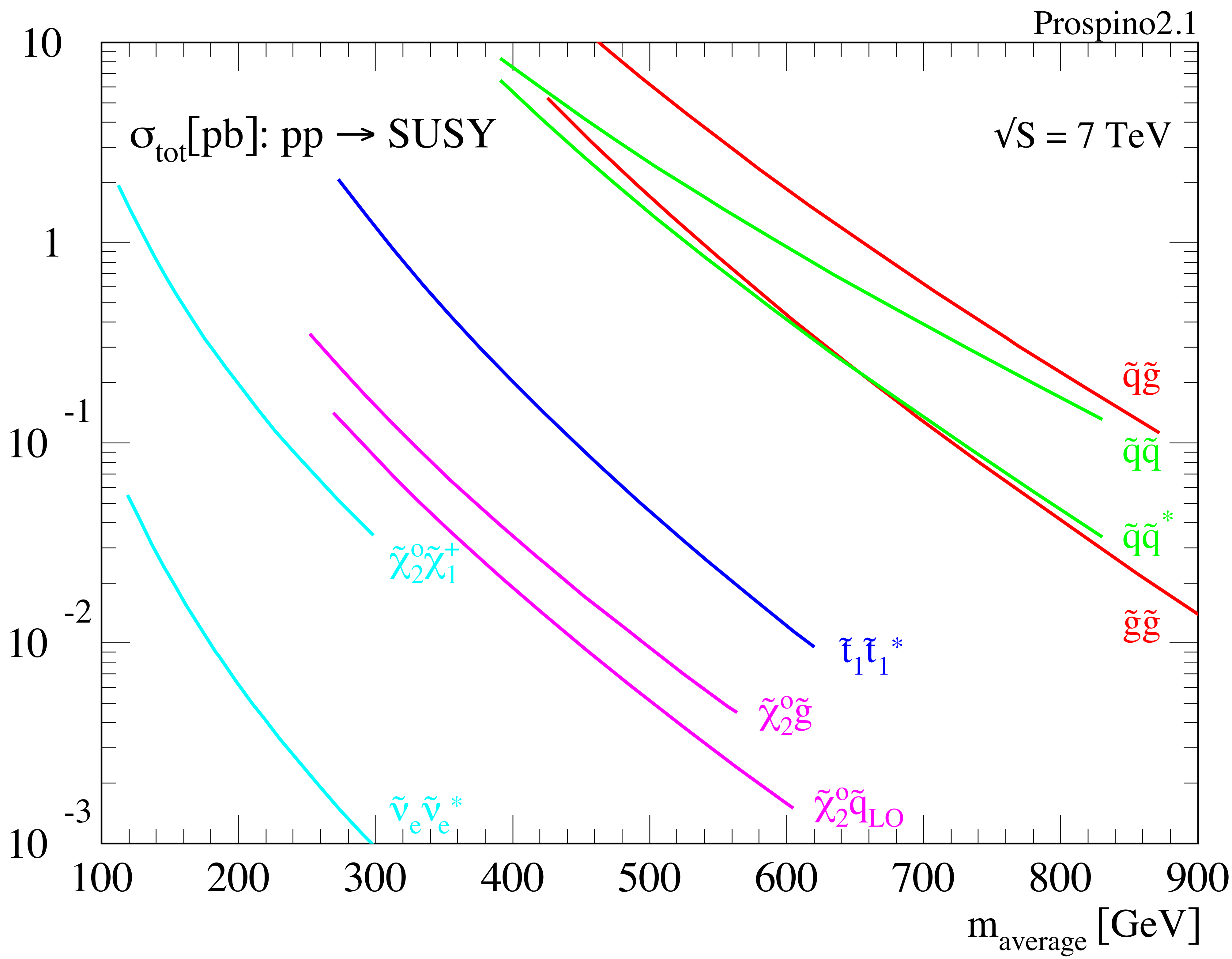
(diagrams not intended to be exhaustive)



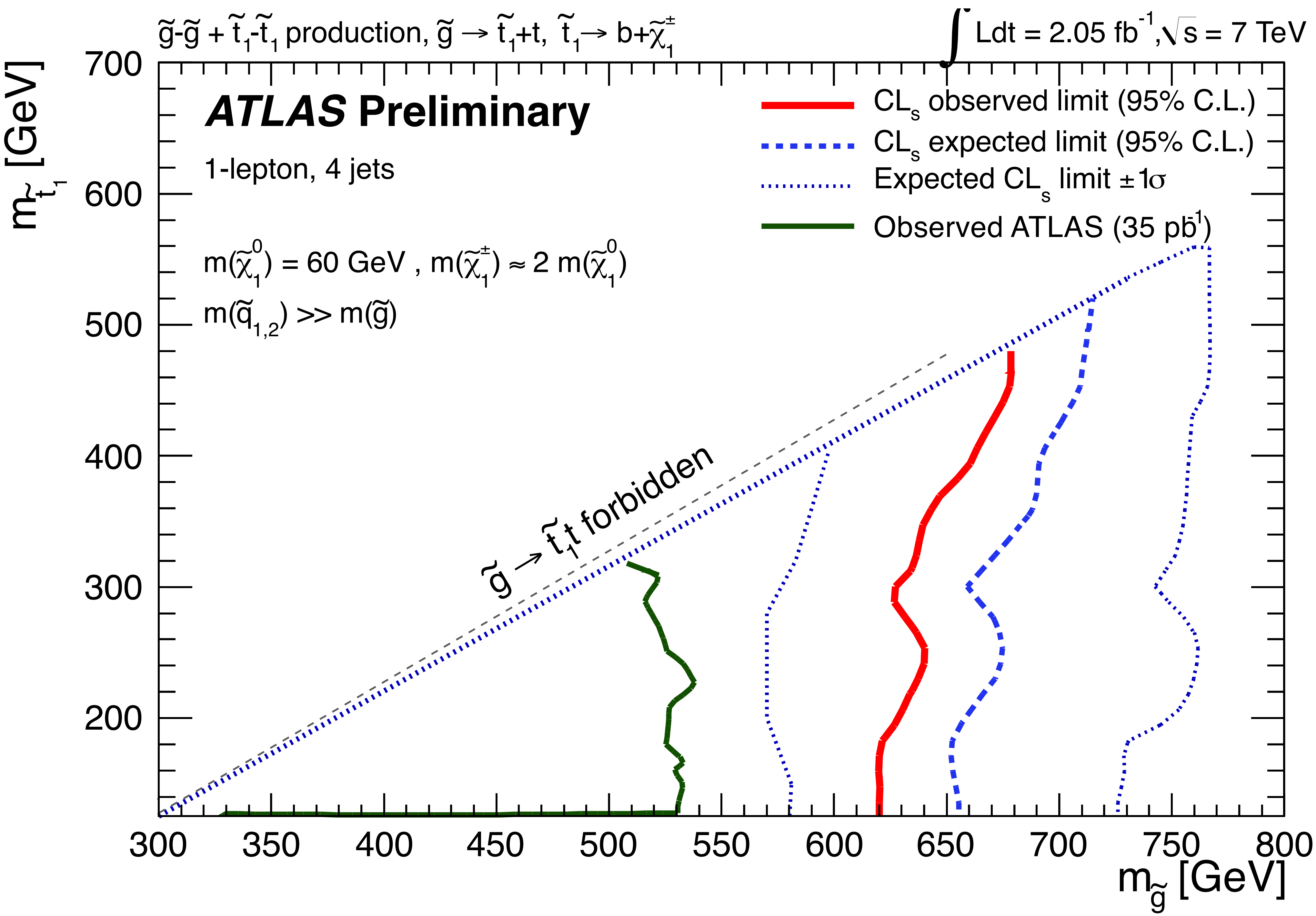
These processes are dominated by *first-generation* squarks

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

How much better can we do?



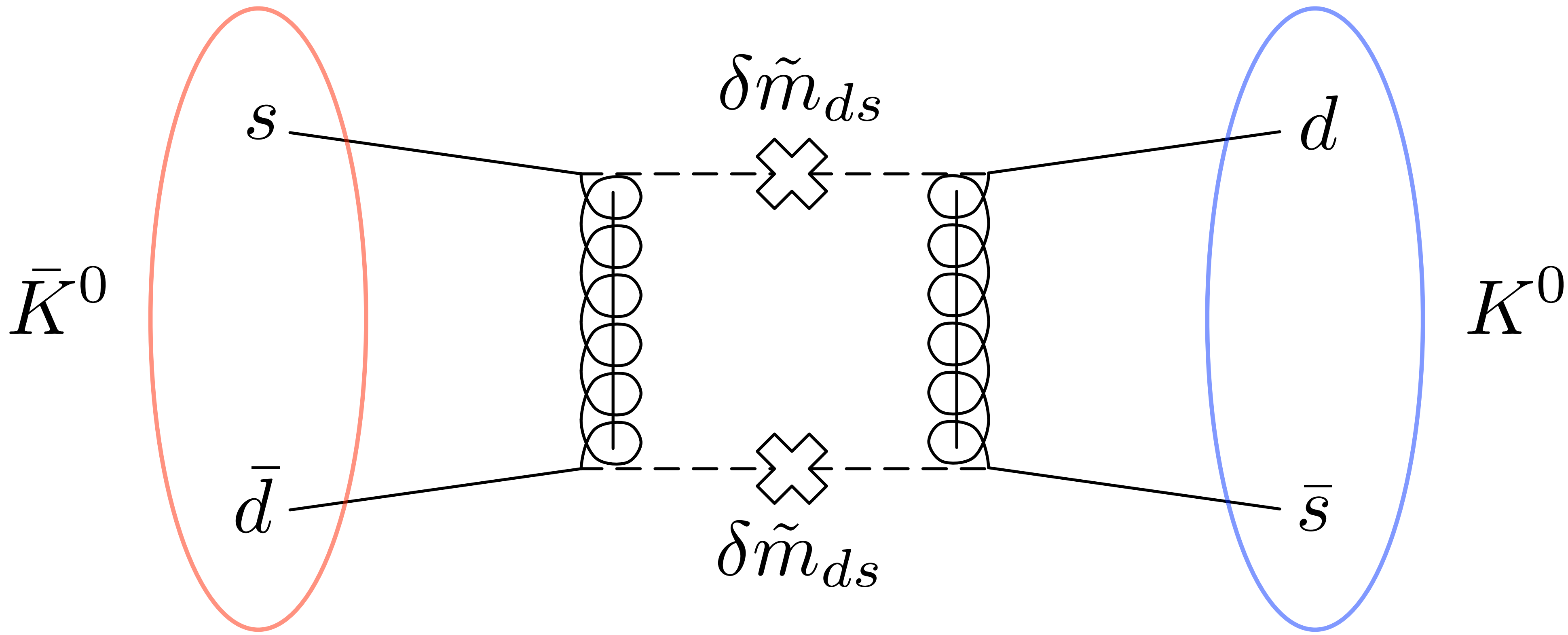
How sharp are the limits w/out the 1st generation?



[See also: theory-side reanalysis of 1/fb SUSY limits by Kats, Meade, Reece, Shih; Essig, Izaguirre, Kaplan, Wacker;Papucci, Ruderman, Weiler; Brust, Katz, Lawrence, and Sundrum]

The trouble with sflavor

A strong constraint on SUSY models; any significant inter-generational mixing in the soft masses leads to prohibitive contributions to FCNCs



Remedies include universality; alignment; or decoupling. Universality is typically simplest & easiest to realize.

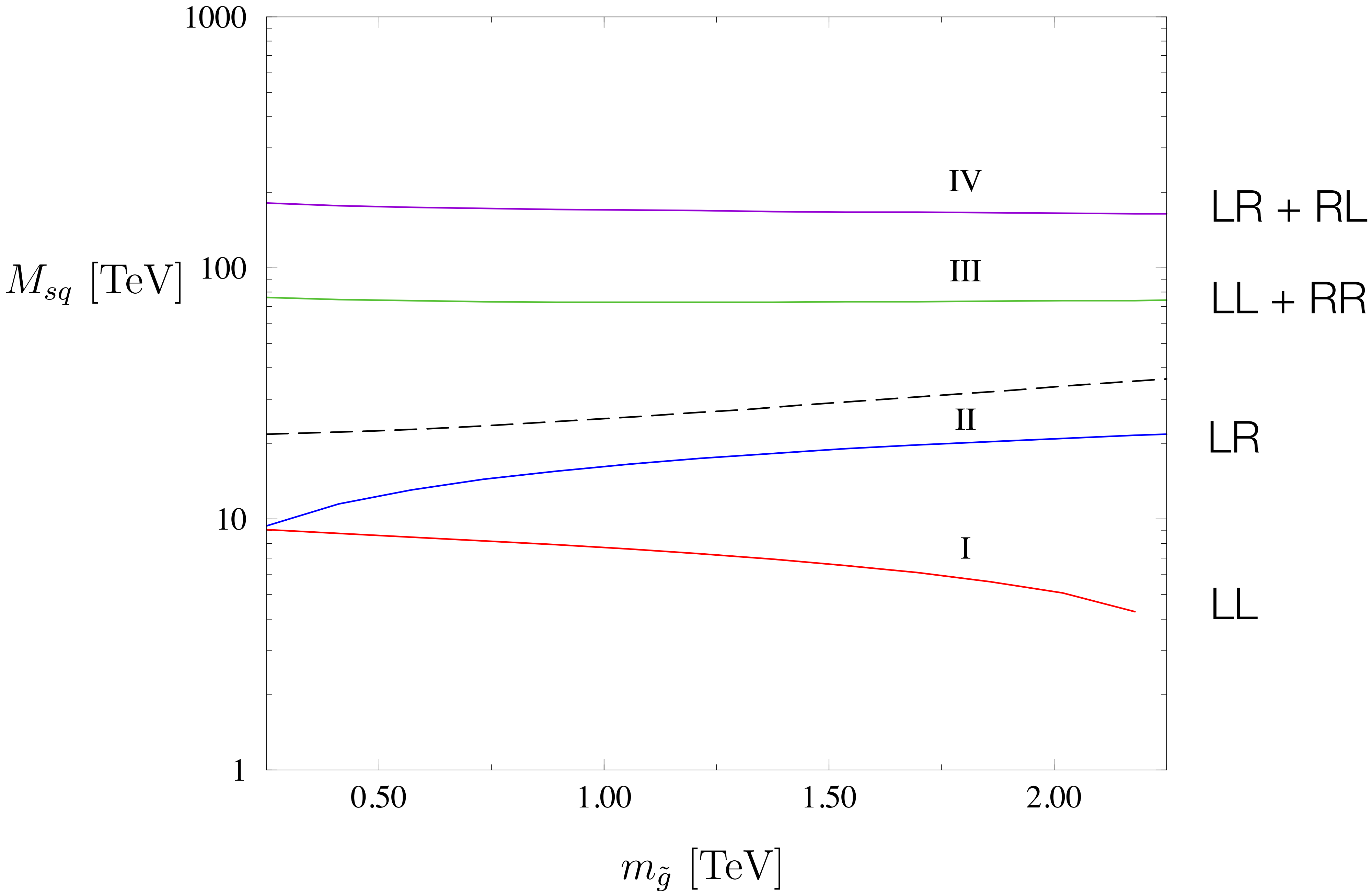
Flavor searches

Decades of precise measurements of meson mixing/decays and other rare processes have strongly constrained new contributions to flavor-violating dimension-6 operators

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}
$(\bar{t}_L\gamma^\mu u_L)^2$	12		7.1×10^{-3}		$pp\to tt$

[Gedalia & Perez]

How degenerate?



$\mathcal{O}(\sin\theta_C)$ alignment

[Contino & Scimemi]

Natural supersymmetry and its discontents

- Natural supersymmetry compatible with LHC limits if third-generation scalars are much lighter than first- and second-generation scalars.

- An old idea, originally motivated in the LEP era by flavor considerations; heavy scalars conveniently suppress K-K mixing and other rare FCNC processes. [Dimopoulos & Giudice; Cohen, Kaplan, Nelson]

- But what worked in the early 90's doesn't work today; simply making 1st- and 2nd-generation scalars heavy doesn't adequately decouple flavor problems! Flavor requires us to preserve an approximate U(2) symmetry acting on these soft masses.

- Somehow SUSY breaking needs to know a bit about flavor, but not too much. And ideally in such a way that's directly tied to the SM flavor structure...

Flavor mediation

We can intimately relate sflavor and flavor by communicating SUSY breaking through a (gauged) Standard Model flavor symmetry.

The point is that gauged SM flavor symmetries must be spontaneously broken to generate SM Yukawas. If these symmetries are broken around the same scale as messengers of SUSY breaking, the 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 benefits...*

First, some Higgsed gauge mediation

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

Only interested in the usual trivial hidden-sector dynamics, and happy with capturing the leading behavior in F/M; work in the spurion limit

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

where now the vector fields also have a supersymmetric mass M_V^2

The usual tricks for avoiding a two-loop calculation won't work. Analytic continuation of the visible-sector wavefunction renormalization sees massless fields above the scale of higgsing and infinitely massive fields below.

The contributions from finite mass are in some sense a *threshold effect.*

Looks like a two-loop calculation is in order...

Option A [Gorbatov, Sudano '08]

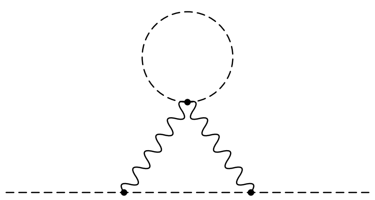


Diagram 1

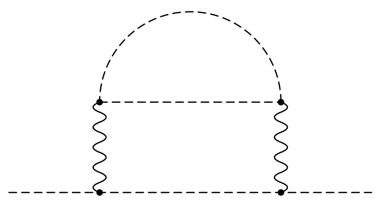


Diagram 2

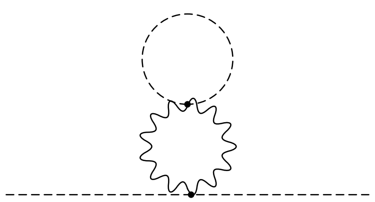


Diagram 3

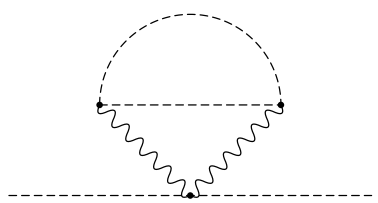


Diagram 4

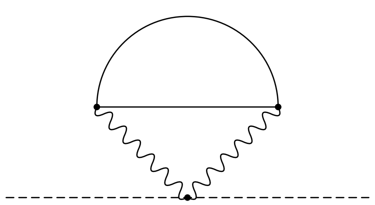


Diagram 5

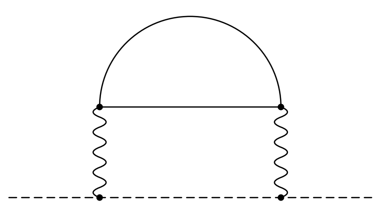


Diagram 6

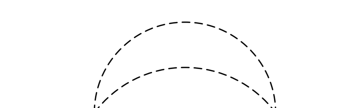


Diagram 7

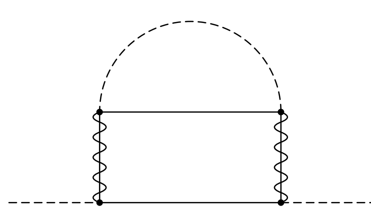


Diagram 8

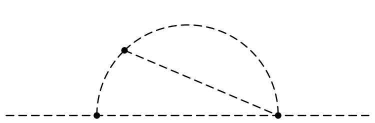


Diagram 9

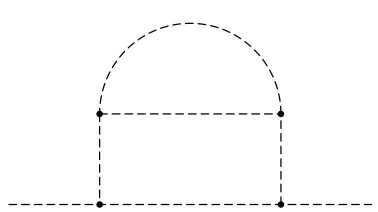


Diagram 10

Compute 10 two-loop diagrams with massive vector bosons

Finally, the sum of unmixed diagrams normalized so that $f(0,0)=1$ gives the function in (2.3):

$$\begin{aligned} f(x,y) = \frac{1}{x^2}\Big[&F(1,y) + (1+y)F\Big(\frac{1}{y},\frac{1}{y}\Big) - F(1+x,y) + \frac{1}{2}(1+x)F\Big(1,\frac{y}{1+x}\Big) \\ &- (1+x)F\Big(\frac{1}{1+x},\frac{y}{1+x}\Big) + \frac{1}{2}(1+x)F\Big(\frac{1-x}{1+x},\frac{y}{1+x}\Big) + (x-2y)F\Big(\frac{1+x}{y},\frac{1}{y}\Big) \\ &- \Big(1+x-\frac{y}{2}\Big)F\Big(\frac{1+x}{y},\frac{1+x}{y}\Big) + \frac{y}{2}F\Big(\frac{1+x}{y},\frac{1-x}{y}\Big)\Big] + (x\to -x), \end{aligned} \tag{A.13}$$

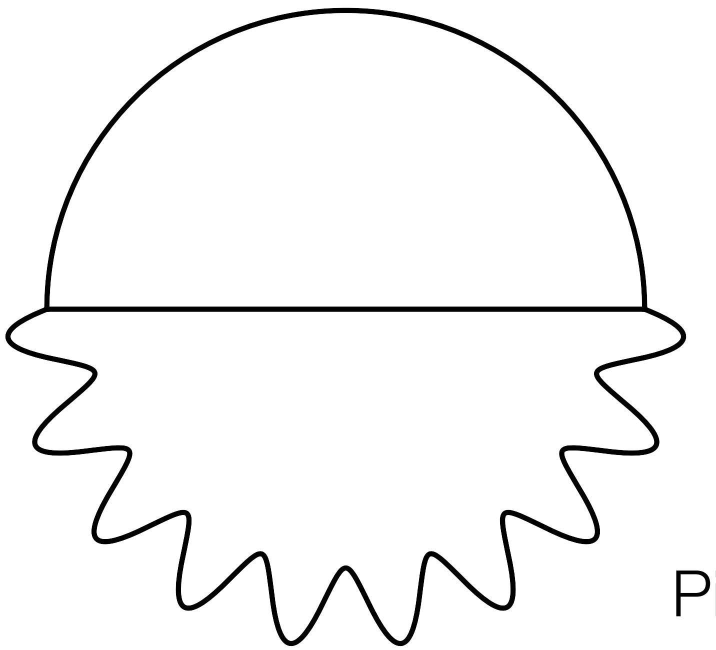
and the sum of the mixed diagrams gives,

$$\begin{aligned} h(x,y,z) = \Big\{\frac{1}{2x^2(y-z)}\Big[&2(2+y)F(1,y) + (2+y)yF\Big(\frac{1}{y},\frac{1}{y}\Big) + 2(x-y)F(1+x,y) \\ &- (1+x)(4+4x-y)F\Big(1,\frac{y}{1+x}\Big) + 2(1+x)(x-y)F\Big(\frac{1}{1+x},\frac{y}{1+x}\Big) \\ &+ (1+x)yF\Big(\frac{1-x}{1+x},\frac{y}{1+x}\Big) + 2(x-y)yF\Big(\frac{1+x}{y},\frac{1}{y}\Big) \\ &- (4+4x-y)\frac{y}{2}F\Big(\frac{1+x}{y},\frac{1+x}{y}\Big) + \frac{y^2}{2}F\Big(\frac{1+x}{y},\frac{1-x}{y}\Big)\Big] + (x\to -x)\Big\} + (y\leftrightarrow z), \end{aligned} \tag{A.14}$$

$$\begin{aligned} F(a,b) = &-\frac{1}{2}\ln^2 a - \mathrm{Li}_2\Big(\frac{a-b}{a}\Big) \\ &+ \Big(\frac{a+b-1}{2r} - \frac{1}{2}\Big)\Big[\mathrm{Li}_2\Big(\frac{b-a}{x_+}\Big) - \mathrm{Li}_2\Big(\frac{a-b}{1-x_+}\Big) - \mathrm{Li}_2\Big(\frac{1-x_+}{-x_+}\Big) + \mathrm{Li}_2\Big(\frac{-x_+}{1-x_+}\Big)\Big] \\ &- \Big(\frac{a+b-1}{2r} + \frac{1}{2}\Big)\Big[\mathrm{Li}_2\Big(\frac{b-a}{x_-}\Big) - \mathrm{Li}_2\Big(\frac{a-b}{1-x_-}\Big) - \mathrm{Li}_2\Big(\frac{1-x_-}{-x_-}\Big) + \mathrm{Li}_2\Big(\frac{-x_-}{1-x_-}\Big)\Big], \end{aligned}$$

Option B [NC, McCullough, Thaler '12]

"Analytically continue" the two-loop effective Kahler potential $|\boldsymbol{M_\Phi}|^2 \equiv \boldsymbol{X}^\dagger \boldsymbol{X}$



$$\left(\boldsymbol{M_V}^2\right)^{ab} = \left(M_V{}^2\right)^{ab} + g'^2 \boldsymbol{q}^\dagger (t_q^a t_q^b + t_q^b t_q^a)\boldsymbol{q}$$

One supergraph contributes to visible soft masses:

$$K_{2L} = -2q_\Phi^2 g'^2 I(|\boldsymbol{M_\Phi}|^2, |\boldsymbol{M_\Phi}|^2, \boldsymbol{M_V}^2)$$

Picking out the terms that yield soft masses leaves

$$K_{2L} \supset \frac{q_\Phi^2 g'^2}{(4\pi)^4}|\boldsymbol{M_\Phi}|^2 \left(2\boldsymbol{\Delta}\log(\boldsymbol{\Delta})\log\left(\frac{|\boldsymbol{M_\Phi}|^2}{\mu^2}\right) + (\boldsymbol{\Delta}+2)\log^2\left(\frac{|\boldsymbol{M_\Phi}|^2}{\mu^2}\right) + \Omega(\boldsymbol{\Delta})\right], \qquad \boldsymbol{\Delta} \equiv \frac{\boldsymbol{M_V}^2}{|\boldsymbol{M_\Phi}|^2}$$

where (there will be a quiz on this at the end)

$$\Omega(\boldsymbol{\Delta}) = \sqrt{\boldsymbol{\Delta}(\boldsymbol{\Delta}-4)}\left(2\zeta(2) + \log^2(\boldsymbol{\alpha}) + 4\mathrm{Li}_2[-\boldsymbol{\alpha}]\right) \qquad \text{with } \boldsymbol{\alpha} = \left(\sqrt{\frac{\boldsymbol{\Delta}}{4}} + \sqrt{\frac{\boldsymbol{\Delta}}{4} - 1}\right)^{-2}.$$

Gives the leading-order (in F/M) soft masses for higgsed gauge mediation, in agreement with the explicit two-loop calculation, but much more compactly.

Soft masses in higgsed GM

One "shift-enter" later...

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

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

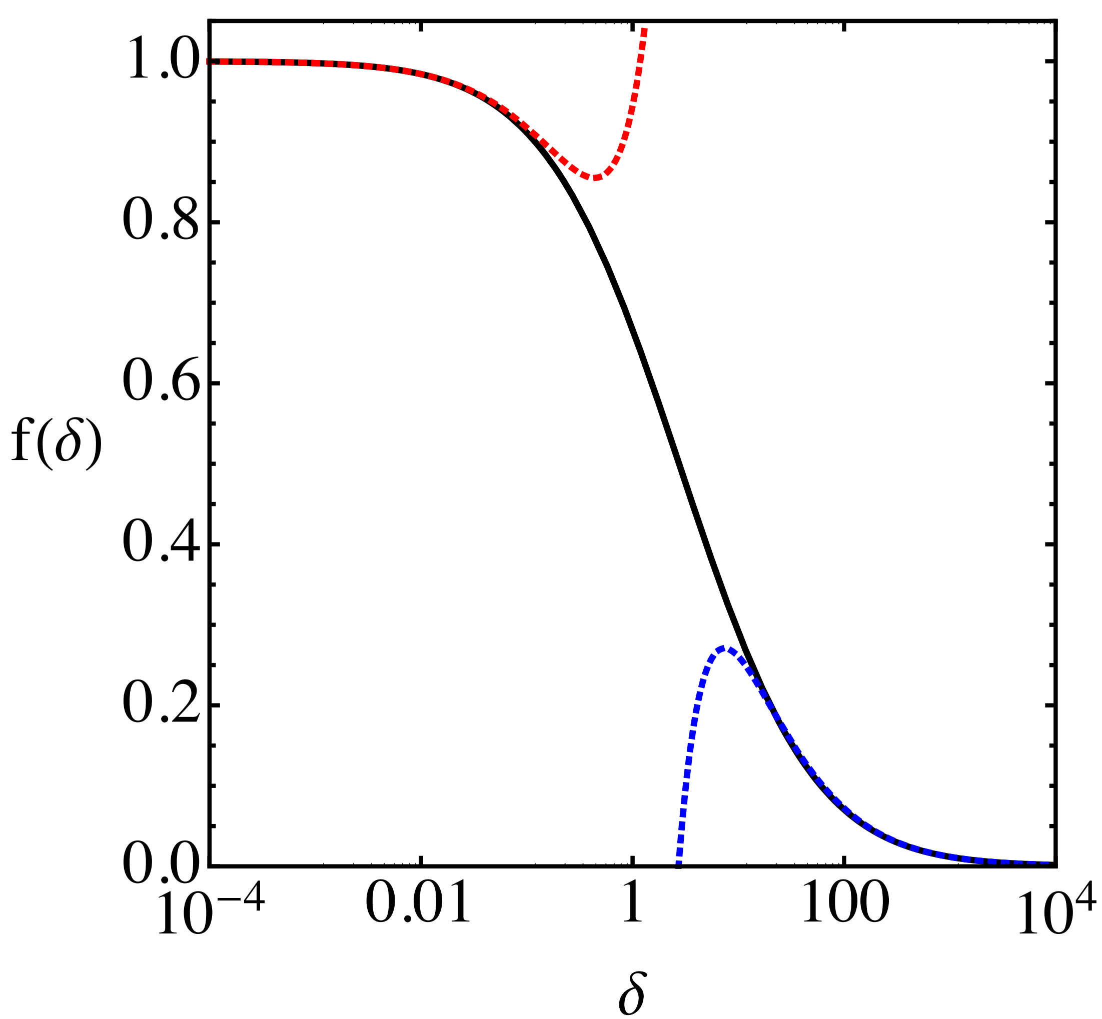
$$f(\delta) = 2\frac{\delta(4-\delta)((4-\delta)+(\delta+2)\log(\delta)) + 2(\delta-1)\Omega(\delta)}{\delta(4-\delta)^3}$$

This result captures the leading order in *F/M* and all orders in *M_V/M*

Asymptotics of higgsed GM

Asymptotic behavior is as expected:

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



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 flavor symmetry of the Standard Model without mixed anomalies?

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

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

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

$$\langle \mathbf{S_u} \rangle = \left(\begin{array}{ccc} v_{u1} & 0 & 0 \\ 0 & v_{u2} & 0 \\ 0 & 0 & v_{u3} \end{array} \right) \qquad \langle \mathbf{S_d} \rangle = V_{\rm CKM} \left(\begin{array}{ccc} v_{d1} & 0 & 0 \\ 0 & v_{d2} & 0 \\ 0 & 0 & v_{d3} \end{array} \right) V_{\rm CKM}^T$$

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

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

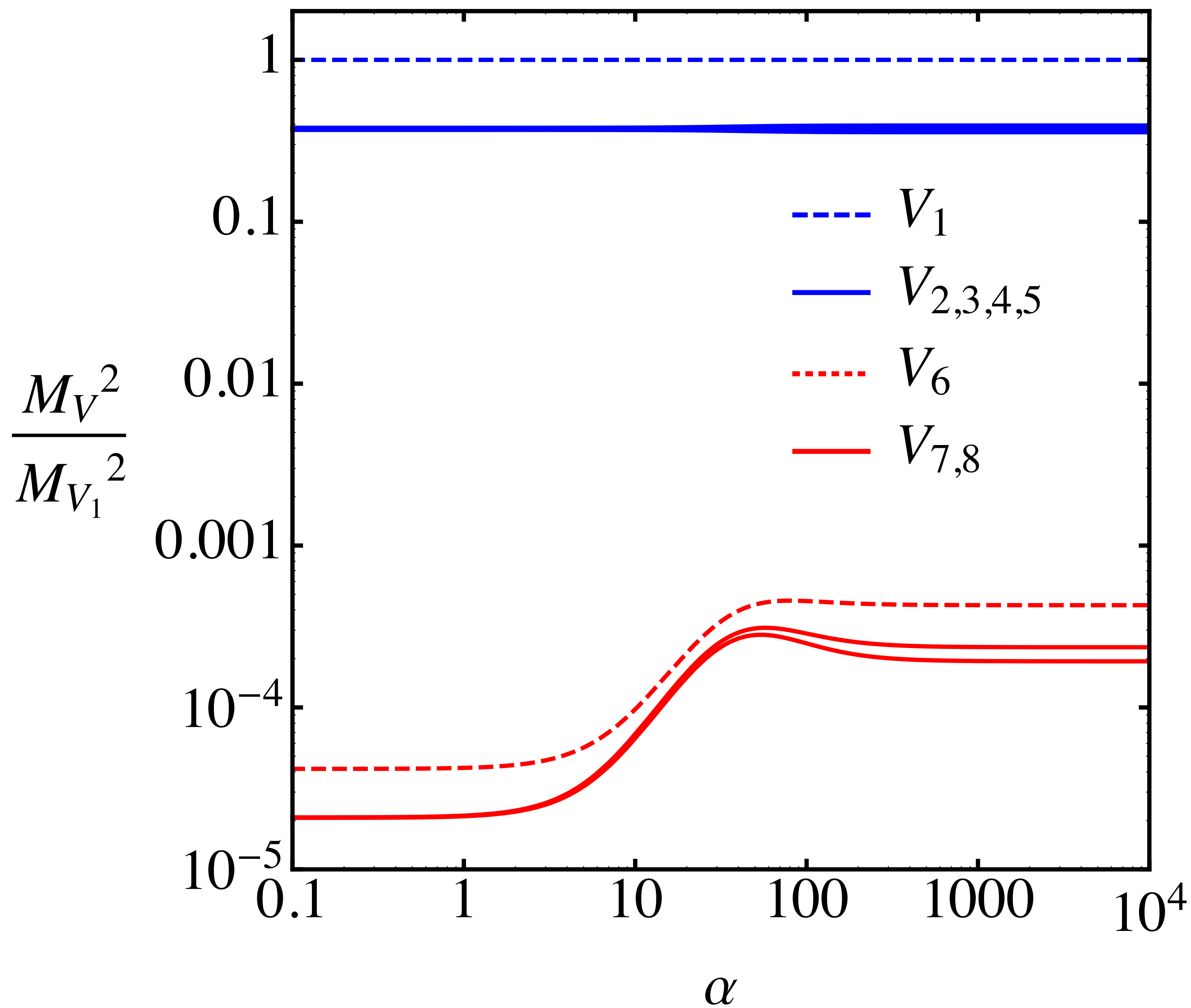
Numerically, including the full pattern of higgsing, these arrange themselves into two sets:

$$M_V^2[\sim \mathrm{SU}(3)_F/\mathrm{SU}(2)_F] \;=\; g_F^2 v_F^2 \{2.67, 1.02, 1.00, 1.00, 0.99\},$$

$$M_V^2[\sim \mathrm{SU}(2)_F] \;=\; g_F^2 v_F^2 \{1.13, 0.57, 0.57\} \times 10^{-4}.$$

The magic of SU(3)

Spectrum of gauge bosons normalized to most massive:



Breaking pattern is approximately

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

followed by

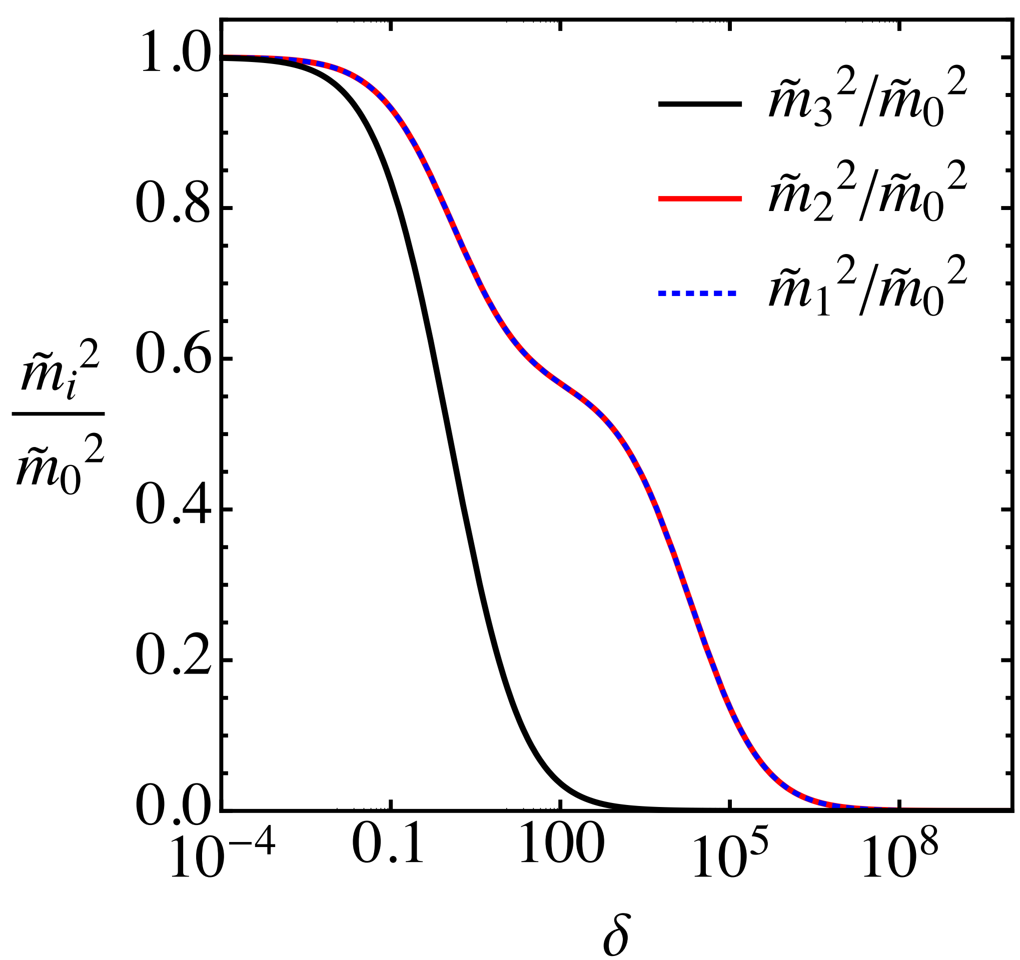
$$\mathrm{SU}(2)_F \longrightarrow \emptyset$$

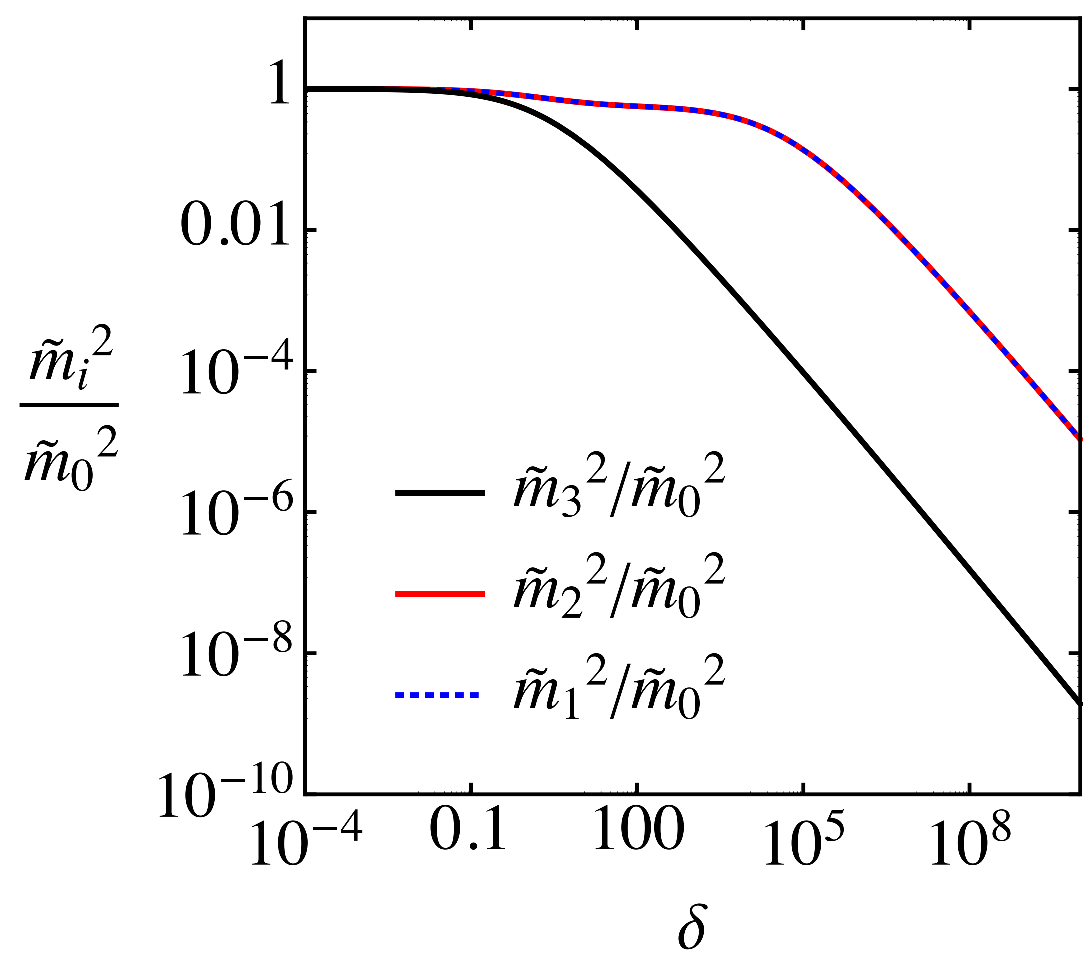
The key feature: SU(3) is rank-2

Soft masses in flavor mediation

This pattern of Higgsing feeds into soft masses via

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





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

Off-diagonal soft masses

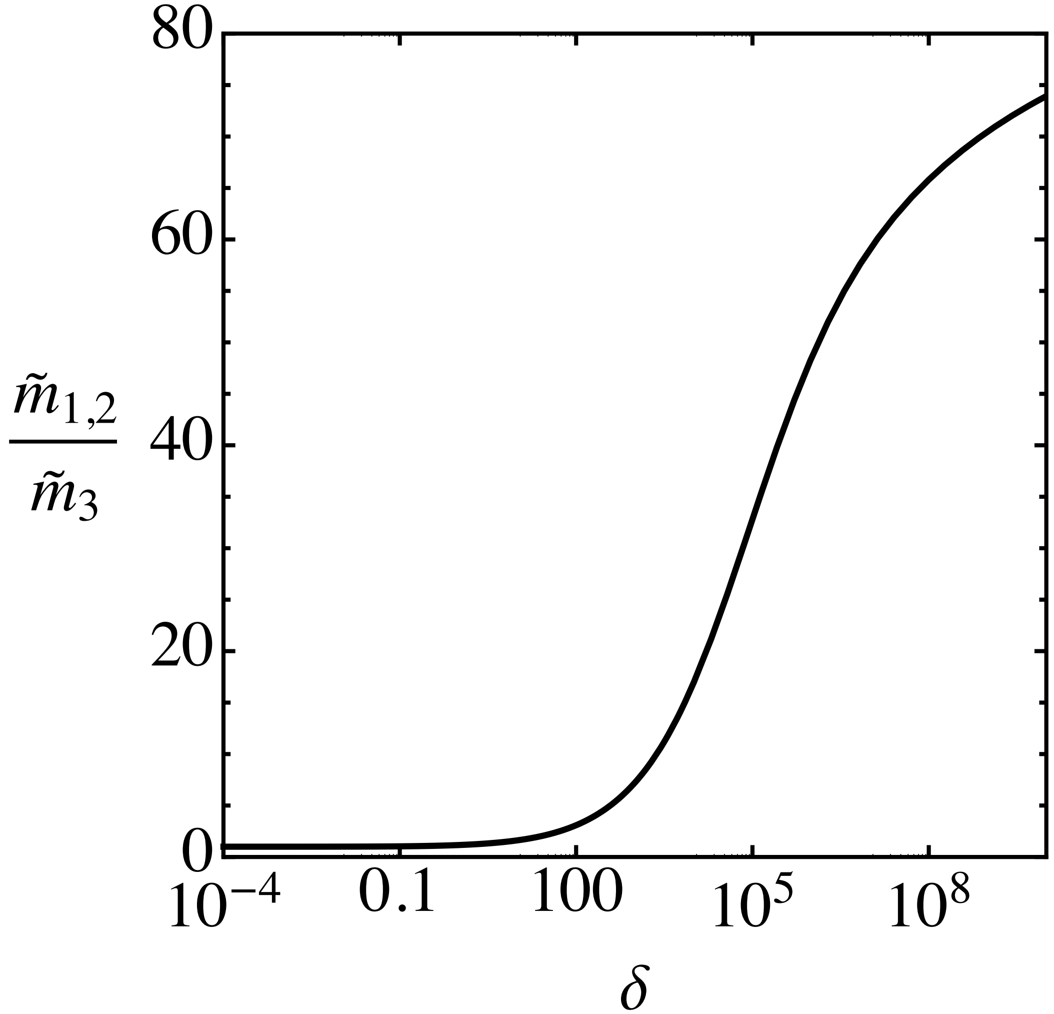
Of course, there are also off-diagonal soft masses, but these are parametrically suppressed:

$$\tilde{m}^2 \approx \begin{pmatrix} \tilde{m}_2^2 & 0 & 0 \\ 0 & \tilde{m}_2^2 & 0 \\ 0 & 0 & \tilde{m}_3^2 \end{pmatrix} + (\tilde{m}_2^2 - \tilde{m}_3^2)\frac{v_{d3}^2}{v_{u3}^2 + v_{d3}^2} \begin{pmatrix} 0 & 0 & \cos(\delta)V_{13} \\ 0 & 0 & V_{23} \\ \cos(\delta)V_{13} & V_{23} & 0 \end{pmatrix}$$

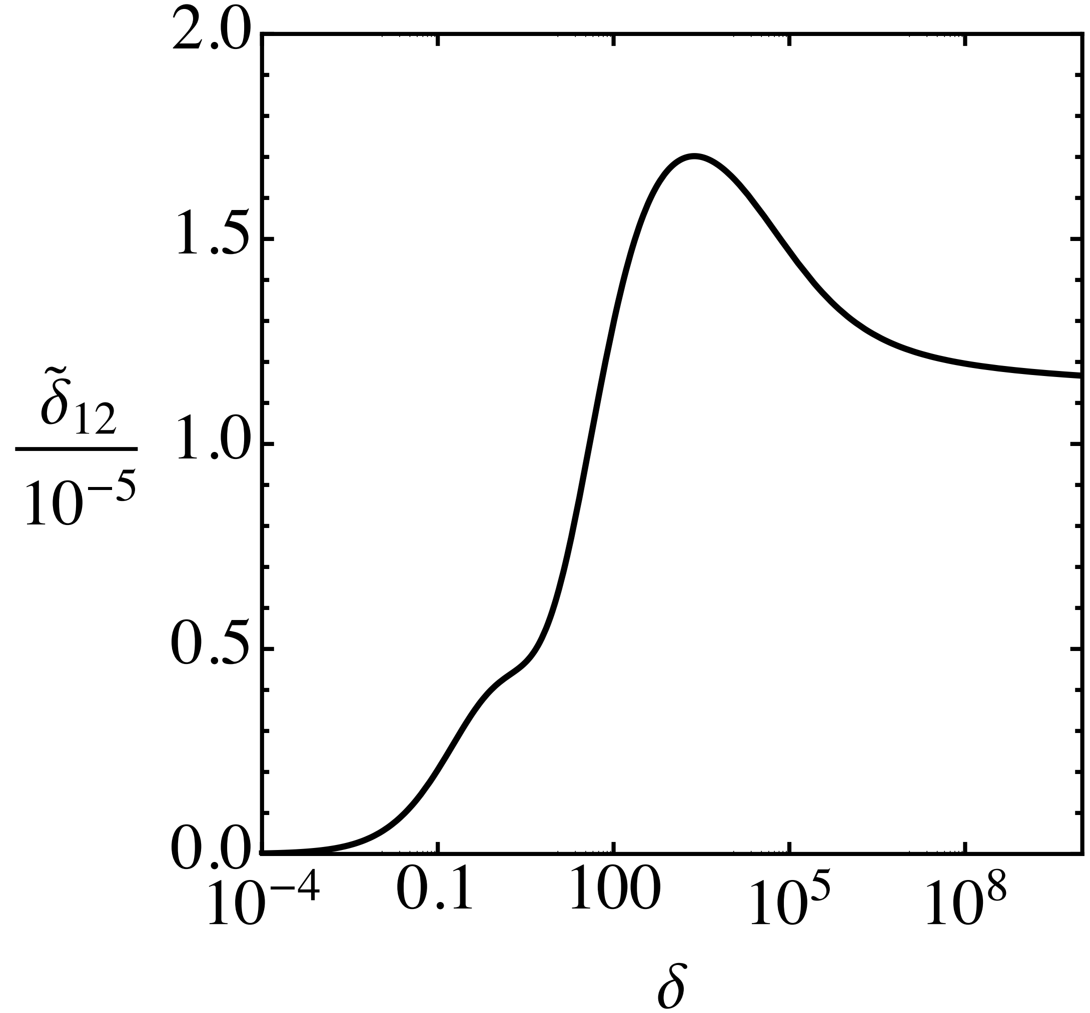
From an FCNC standpoint, these are much smaller than the usual mixings that come from rotating to the fermion mass eigenbasis

To very high fidelity, we have an automatic *U(2)* sflavor symmetry because *SU(3)* is rank-2.

How well do we do?



Hierarchy



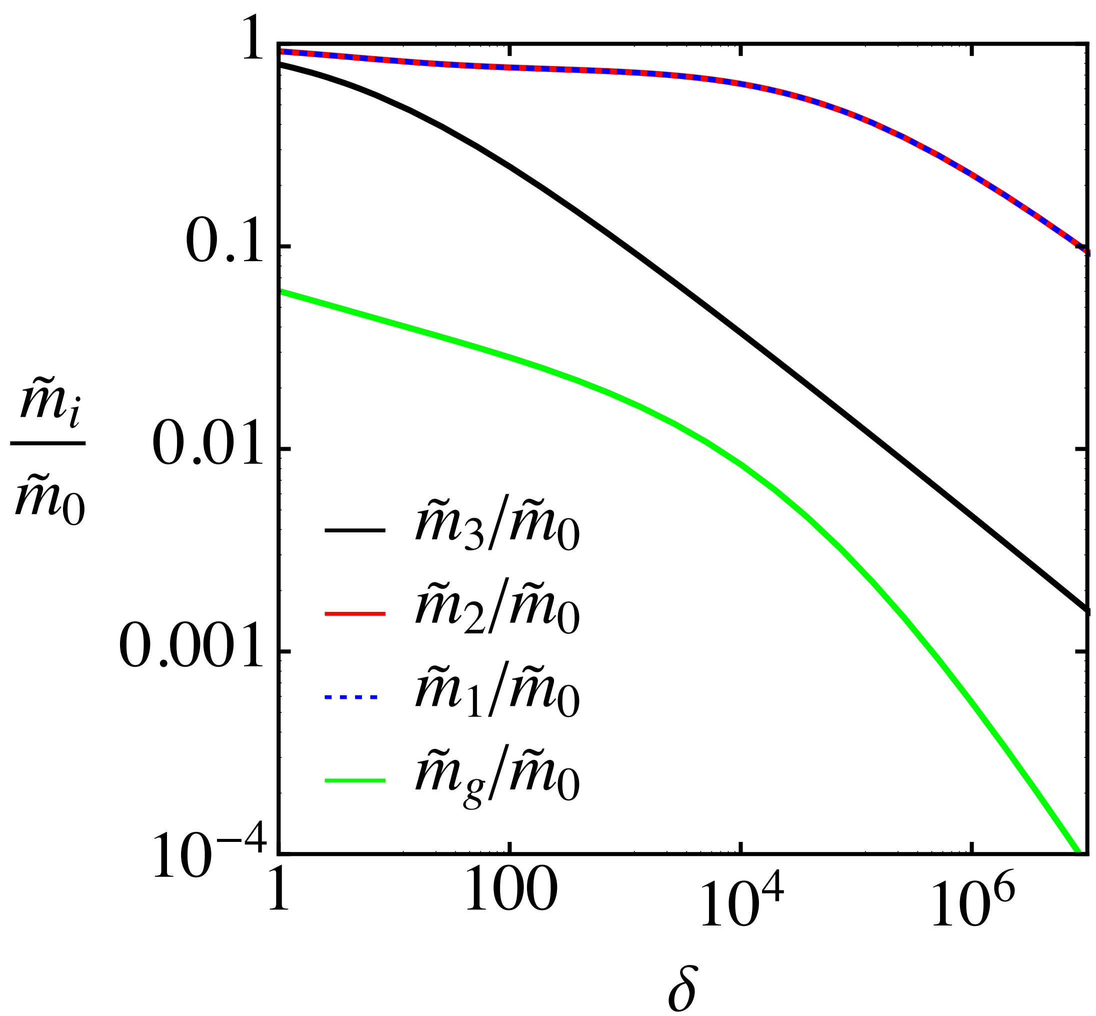
U(2) symmetry

What about the...

Gauginos of the SM gauge group?*

We communicated SUSY breaking via gauge mediation, but not of SU(3) x SU(2) x U(1); at leading order the MSSM gauginos are massless.

There is a source of gaugino masses, but it comes in at three loops:



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 less of an issue

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. This can be achieved by adding singlets, etc., but I won't focus on the details.

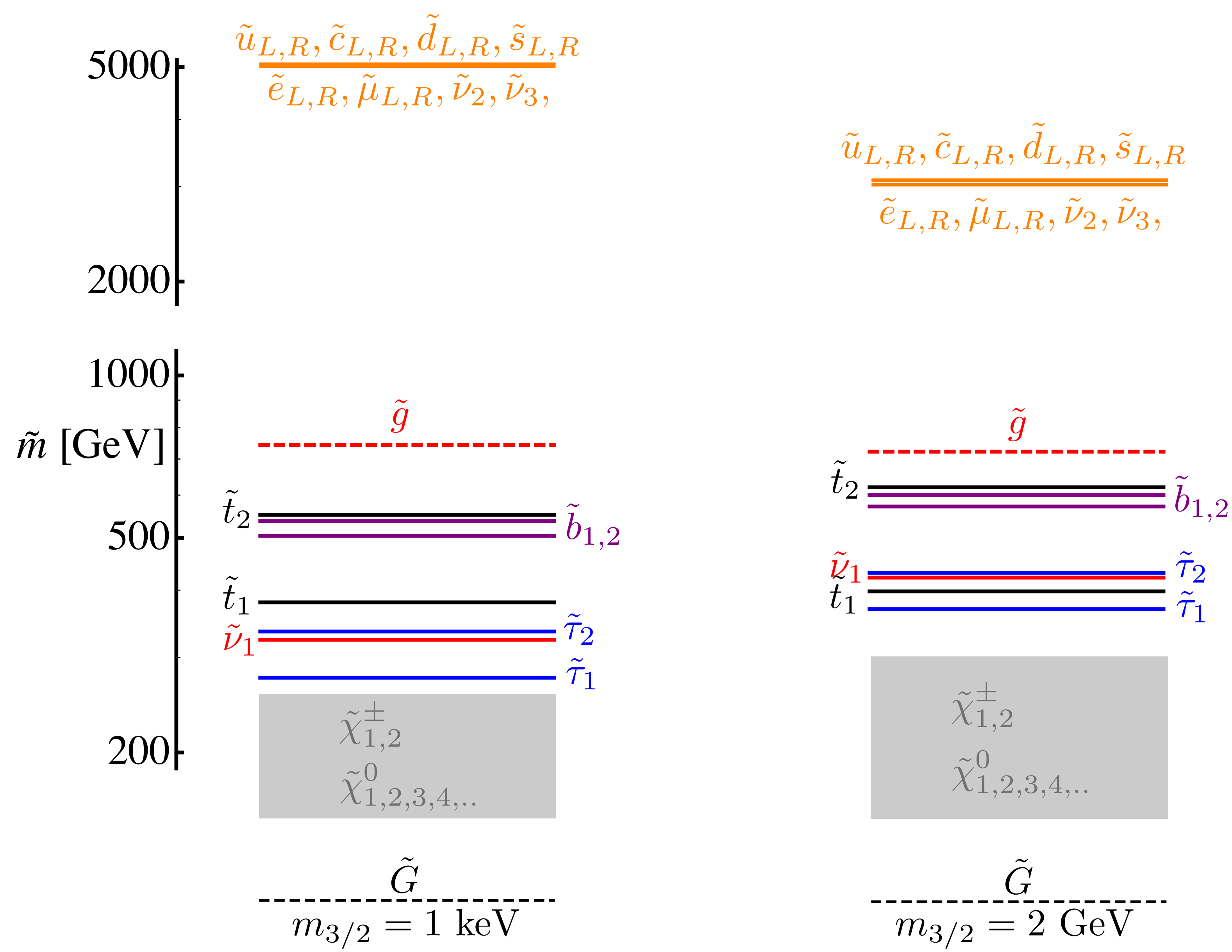
A few examples

Benchmark	M [GeV]	$\sqrt{C_F(\mathbf{\Phi})}\alpha_F(M)$	$\sqrt{\delta}$	$\tilde{m}^F_{1,2}$ [GeV]	$\tilde{m}^F_3$ [GeV]	$m_{\tilde{g}}$ [GeV]	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{\tau}}$
Low Scale	5×10^7	0.61	92	5000	250	743	380	
High Scale	10^{14}	0.31	35	3000	300	722	398	

Gauge mediation from flavor + mGMSB

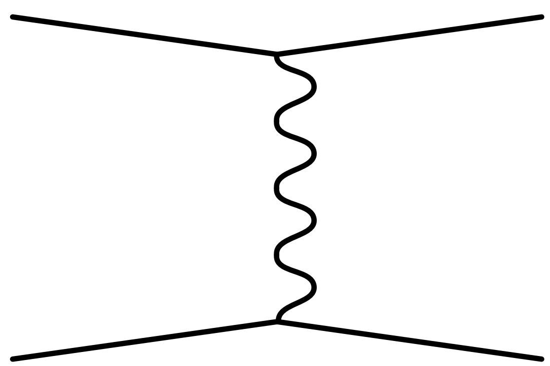
F/M = 85 TeV

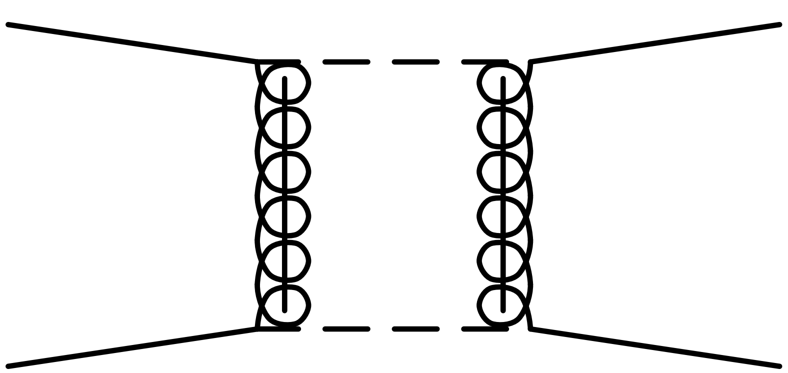
Third generation masses lowered by 2-loop RG



What about FCNCs?

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

$$v_{u2} \gtrsim 500\,\mathrm{TeV}\ (7500\,\mathrm{TeV})$$

Without (with) O(1) new CPV
No problem given the scales we're interested in.

One-loop FCNC

Strongly protected from one-loop SUSY FCNCs

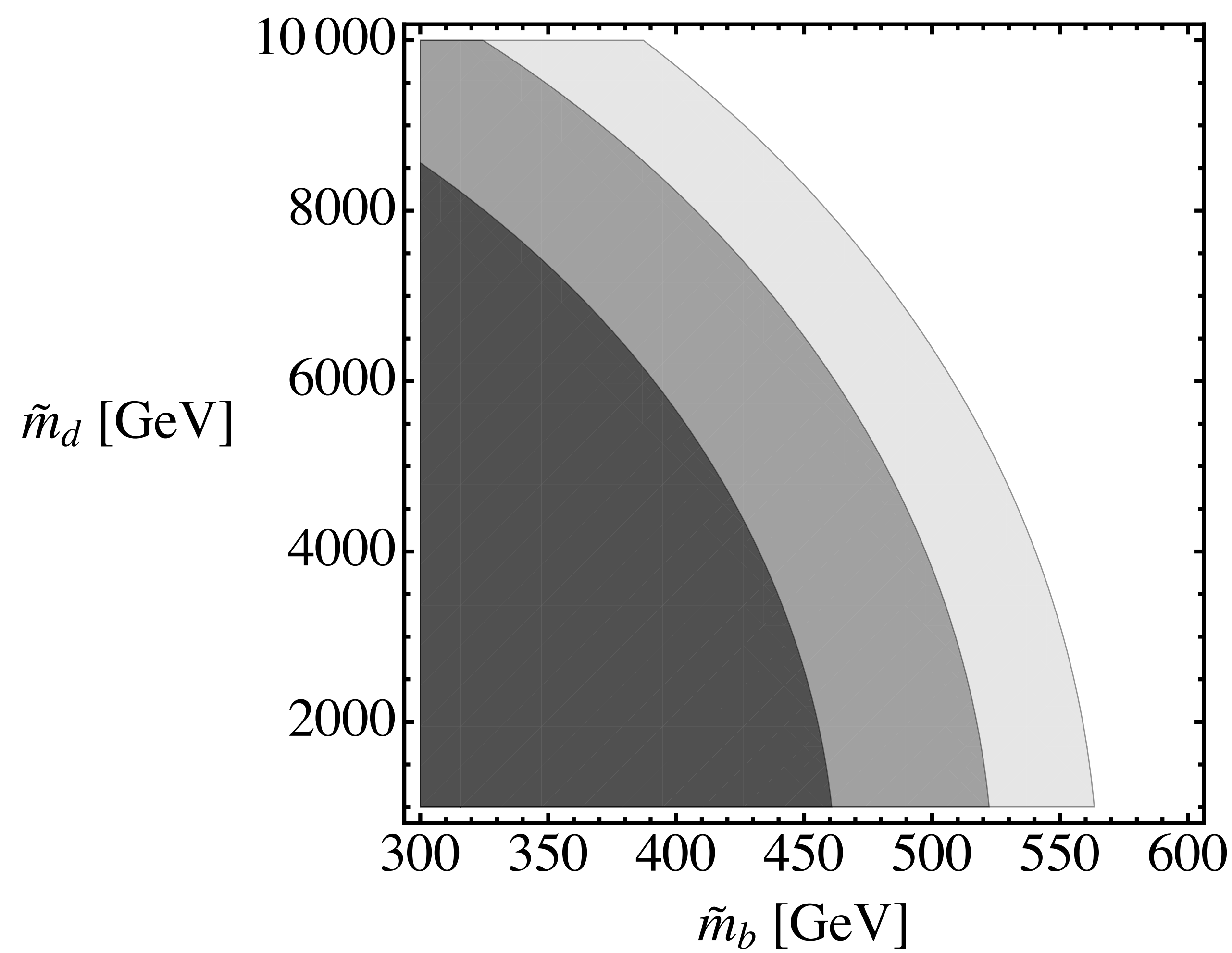
U(2) sflavor symmetry plus heavy 1st, 2nd generation scalars means usual K-K mixing diagram is tiny

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.



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.

Future directions

- We've considered the simplest anomaly-free gauged flavor symmetry, and the simplest mechanism for spontaneous symmetry breaking; other possibilities could yield novel phenomenology.

- Perhaps there's a clever way of generating MSSM gaugino masses intrinsic to the flavor mediation mechanism, at weak or strong coupling.

- Various possible extensions, particularly from the flavor sector. E.g., F-term expectation values in the flavor sector could lead to large A-terms, with corresponding enhancement of the Higgs mass.

- Easy to envision a generalized framework for flavor mediation along the lines of General Gauge Mediation; many of the necessary ingredients already exist...

Conclusions

- The first year of LHC data has imperiled light SUSY with universal masses; this paradigm is beginning to look either unnatural or incorrect.
- Naturalness is preserved if the third generation is significantly lighter than the first two, provided an approximate sflavor symmetry protects against FCNC.
- These features are automatically realized via flavor mediation; the soft spectrum is directly connected to the flavor spectrum via higgsed gauge mediation
- Although sflavor knows about flavor, a U(2) sflavor symmetry arises due to the rank of the gauged flavor group.
- Apart from the strong LHC motivation, mediating SUSY breaking through gauged nonabelian flavor symmetries is new and relatively unexplored; many possible model-building directions to pursue...

Thank you!