Extra vector-like matter and the Higgs mass in supersymmetry

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Based on `0910.2732`.

Supersymmetry is “too big to fail”

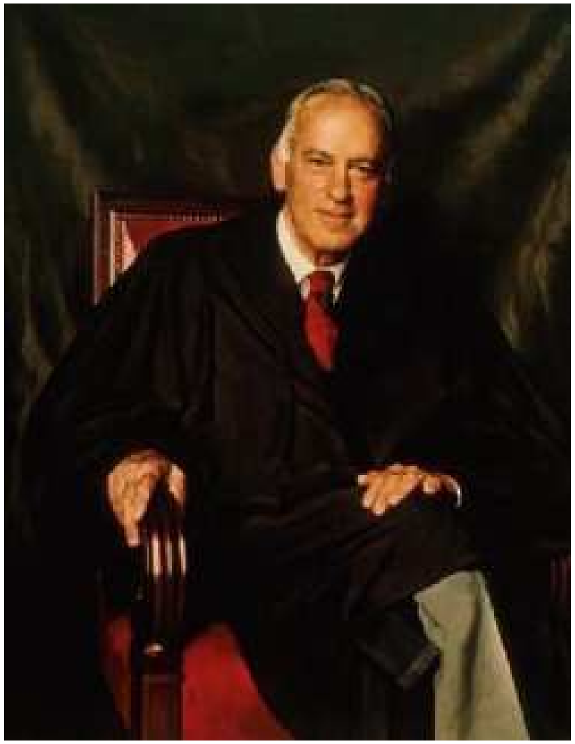
- A solution to the hierarchy problem
- A dark matter candidate
- Gauge coupling unification

However, the non-discovery of the lightest Higgs boson h^0 at LEP2 is cause for doubt.

The supersymmetric little hierarchy problem is the fear that some percent-level fine-tuning is needed to explain why $M_{h^0} > 114$ GeV in most supersymmetric models.

What is fine tuning?

“I shall not today attempt further to define [it]... and perhaps I could never succeed in intelligibly doing so. **But I know it when I see it...**”



U.S. Supreme Court Justice Potter Stewart concurrence in *Jacobellis v. Ohio* (1964).

Like pornography, fine-tuning is impossible to define.

But, like Potter Stewart, I usually know it when I see it.

The models I'm going to discuss today are motivated by the desire to be less fine-tuned than the MSSM.

Whether they succeed is a debatable question, to be decided by the Supreme Court of the Universe.

Simplified form of SUSY prediction:

$$M_h^2 \;=\; m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} y_t^2 m_t^4 \sin^2\!\beta \,\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

Top squarks are spin-0 partners of top quark: $\tilde{t}_1$, $\tilde{t}_2$.

$\tan\beta = v_u/v_d$ = ratio of Higgs VEVs.

To evade discovery at LEP2, need $\sin\beta \approx 1$ and (naively)

$$\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \;\gtrsim\; 700\ \mathrm{GeV}.$$

The logarithm apparently must be $\;\gtrsim\; 3$.

Meanwhile, the condition for Electroweak Symmetry Breaking is:

$$m_Z^2 \;=\; -2\left(|\mu|^2 + m_{H_u}^2\right) + \text{small loop corrections} \;+\; \mathcal{O}(1/\tan^2\beta).$$

Here $|\mu|^2$ is a SUSY-preserving Higgs squared mass,
$m_{H_u}^2$ is a (negative) SUSY-violating Higgs scalar squared mass.

The problem: typical models for SUSY breaking imply that $-m_{H_u}^2$ is comparable to $m_{\tilde{t}_1} m_{\tilde{t}_2} \;\gtrsim\; (700\ \mathrm{GeV})^2$. If so, then required cancellation is of order 1%.

However, things may not be so bad, for at least three reasons:

- It isn't obvious how $-m^2_{H_u}$ is related to $m_{\tilde{t}_1} m_{\tilde{t}_2}$.

  They are related by SUSY breaking, but in different ways in different models.

- The previous formula for M_h^2 is too simplistic.

  Top-squark mixing can raise M_h^2 dramatically.

- The previous formula for M_h^2 changes in extensions of the minimal SUSY model.

Since $\Delta M_h^2 \propto y_t^4$, try introducing another, new, fermion with a large Yukawa coupling.

An obvious try: a new chiral 4th family (t', b', τ', ν').
However, this presents problems:

- Required Yukawa couplings for the 4th family would be so large (for fermions heavy enough to avoid discovery at Tevatron) that they would be non-perturbative not far above the weak scale. Say goodbye to gauge-coupling unification.
- Precision electroweak boson self-energy corrections would be too large, unless there is some rather lucky cancellation.
  See for example Kribs, Plehn, Spannowsky, Tait 0706.3718.

Instead, consider new extra vector-like quark and lepton supermultiplets. Mostly get their masses from electroweak-singlet mass terms, but also have large Yukawa couplings to the MSSM Higgs fields.

Superpotential sources of mass:

$$W = M_\Phi \Phi \overline{\Phi} + M_\phi \phi \overline{\phi} + k H_u \Phi \overline{\phi} + k' H_d \overline{\Phi} \phi$$

Here $\Phi, \overline{\Phi}$ are $SU(2)_L$ doublet quarks and antiquarks, $\phi, \overline{\phi}$ are corresponding singlet quarks and antiquarks, and k, k' are Yukawa couplings to the MSSM Higgs fields H_u and H_d.

Assume that $M_\Phi, M_\phi \lesssim$ 1 TeV, technically natural just like μ parameter of the MSSM.

Features of this class of models:

- Unification of perturbative gauge couplings still works
  (for appropriate choices of extra superfields)
- Yukawa coupling k has an IR quasi-stable fixed point
- Big positive corrections to M_h^2, proportional to k^4
  (Large vector-like masses break SUSY, **don't** decouple.)
- Moderate corrections to S, T precision electroweak parameters
  (Decouple for large vector-like masses)
- Tevatron and LHC can constrain or discover and explore

Previous work on this idea has been surprisingly sparse.

Notable exceptions:

Moroi, Okada 1992;

Babu, Gogoladze, Kolda 2004;

Babu, Gogoladze, Rehman, Shafi, 2008.

Corrections to the Peskin-Takeuchi T parameter were overestimated by a factor of 4, which we shall see is crucial.

Much less constrained than previously thought!

Outline of remainder of talk:

- Models
- Corrections to M_h^2
- Precision electroweak observable corrections
- Decays of lightest new fermions and collider limits and signals

Requiring perturbative gauge coupling unification, find three models of this type that work.

Two have been discussed by BGRS 2008 and just correspond to adding complete reps of $SU(5)$, namely $\mathbf{5}+\overline{\mathbf{5}}$ and $\mathbf{10}+\overline{\mathbf{10}}$.

A third model is new and is not of that type, but still preserves gauge coupling unification.

LND Model

Extra new chiral superfields = $L,\ \overline{L},\ N,\ \overline{N},\ D,\ \overline{D}$.

Transform under $SU(3)_c \times SU(2)_L \times U(1)_Y$ as

$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ + $(\mathbf{1}, \mathbf{2}, \frac{1}{2})$ + $(\mathbf{1}, \mathbf{1}, 0)$ + $(\mathbf{1}, \mathbf{1}, 0)$ + $(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ + $(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$.

Superpotential:

$$W = M_L L\overline{L} + M_N N\overline{N} + kH_u L\overline{N} + k' H_d \overline{L} N + M_D D\overline{D}.$$

This just consists of a $\mathbf{5} + \overline{\mathbf{5}}$ + singlets of $SU(5)$.

New particles (beyond the MSSM):

Fermions: $b',\ \ \tau',\ \ \nu',\ \ \nu''$.

Scalars: $\tilde{b}'_{1,2},\ \ \tilde{\tau}'_{1,2},\ \ \tilde{\nu}'_{1,2,3,4}$.

QUE Model

Extra new chiral superfields = $Q,\ \overline{Q},\ U,\ \overline{U},\ E,\ \overline{E}$.

Transform under $SU(3)_c \times SU(2)_L \times U(1)_Y$ as

$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$ + $(\overline{\mathbf{3}}, \mathbf{2}, -\frac{1}{6})$ + $(\mathbf{3}, \mathbf{1}, \frac{2}{3})$ + $(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$ + $(\mathbf{1}, \mathbf{1}, -1)$ + $(\mathbf{1}, \mathbf{1}, 1)$.

Superpotential:

$$W = M_Q Q\overline{Q} + M_U U\overline{U} + kH_u Q\overline{U} + k' H_d \overline{Q} U + M_E E\overline{E}.$$

This just consists of a $\mathbf{10} + \overline{\mathbf{10}}$ of $SU(5)$.

New particles (beyond the MSSM):

Fermions: $t',\ \ t'',\ \ b',\ \ \tau'$.

Scalars: $\tilde{t}'_{1,2,3,4},\ \ \tilde{b}'_{1,2},\ \ \tilde{\tau}'_{1,2}$.

QDEE Model

Extra new chiral superfields = $Q,\ \overline{Q},\ D,\ \overline{D},\ E_1,\ E_2,\ \overline{E}_1,\ \overline{E}_2$

Transform under $SU(3)_c \times SU(2)_L \times U(1)_Y$ as

$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$ + $(\overline{\mathbf{3}}, \mathbf{2}, -\frac{1}{6})$ + $(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ + $(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$ +
$2 \times (\mathbf{1}, \mathbf{1}, -1)$ + $2 \times (\mathbf{1}, \mathbf{1}, 1)$.

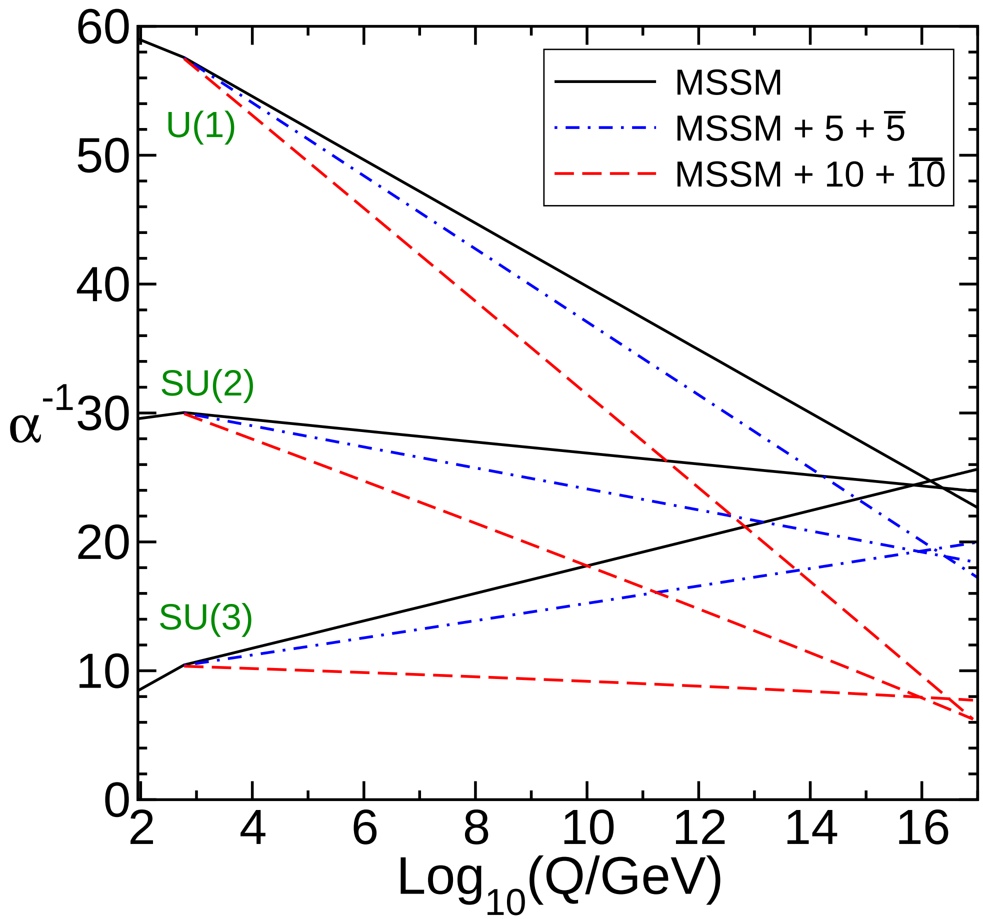
Superpotential:

$$\begin{aligned} W &= M_Q Q\overline{Q} + M_D D\overline{D} + kH_u\overline{Q}D + k'H_d Q\overline{D} \\ &\quad + M_{E_1}E_1\overline{E}_1 + M_{E_2}E_2\overline{E}_2. \end{aligned}$$

This does NOT consist of complete multiplets of of $SU(5)$, but has the same effect on gauge coupling unification as a $\mathbf{10} + \overline{\mathbf{10}}$.

Very similar to QUE model, but the collider phenomenology will be quite different because the lightest new fermion is b' rather than t'.

Gauge couplings still unify above 10^{16} GeV, but at stronger coupling.



Black = MSSM

Blue = LND Model

Red = QUE or QDEE Model

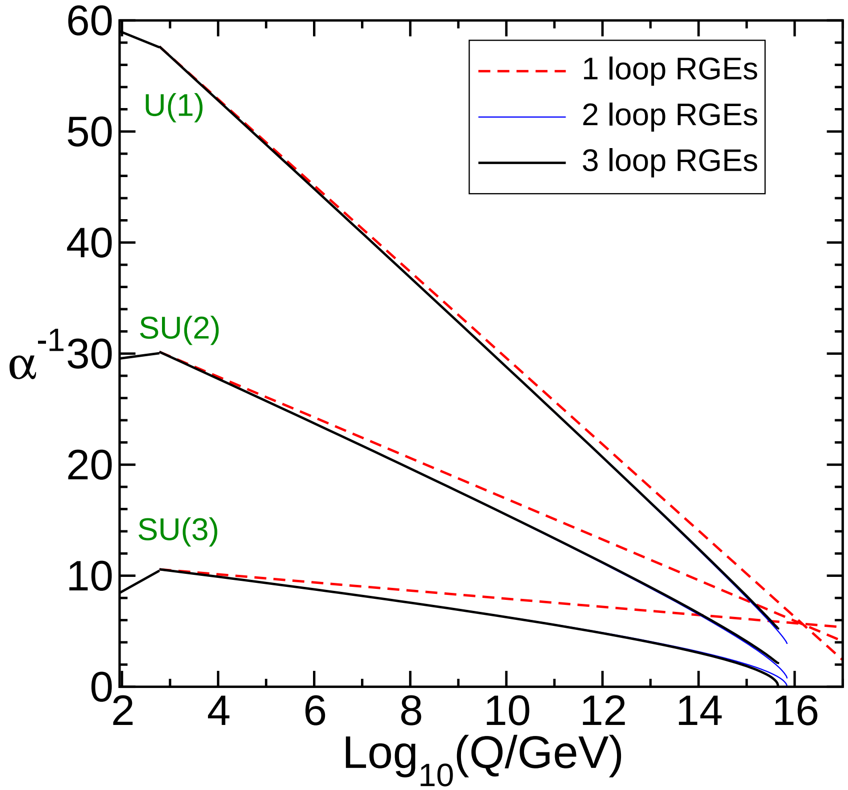
All new particle thresholds taken at $Q = 600$ GeV.

Extra fields contribute equally to the three beta functions.

An aside: why not a complete 4th vector-like family?

Explored by BGRS2008, and very recently by P. Graham, Ismail, Saraswat and Rajendran `0910.2732`, based on a 1-loop analysis.

Unfortunately, taking into account higher-loop effects, perturbative unification fails (unless new particle masses $\gg$ 1 TeV):



For maximum effect on M_h^2, we want the Yukawa coupling k to be as large as possible.

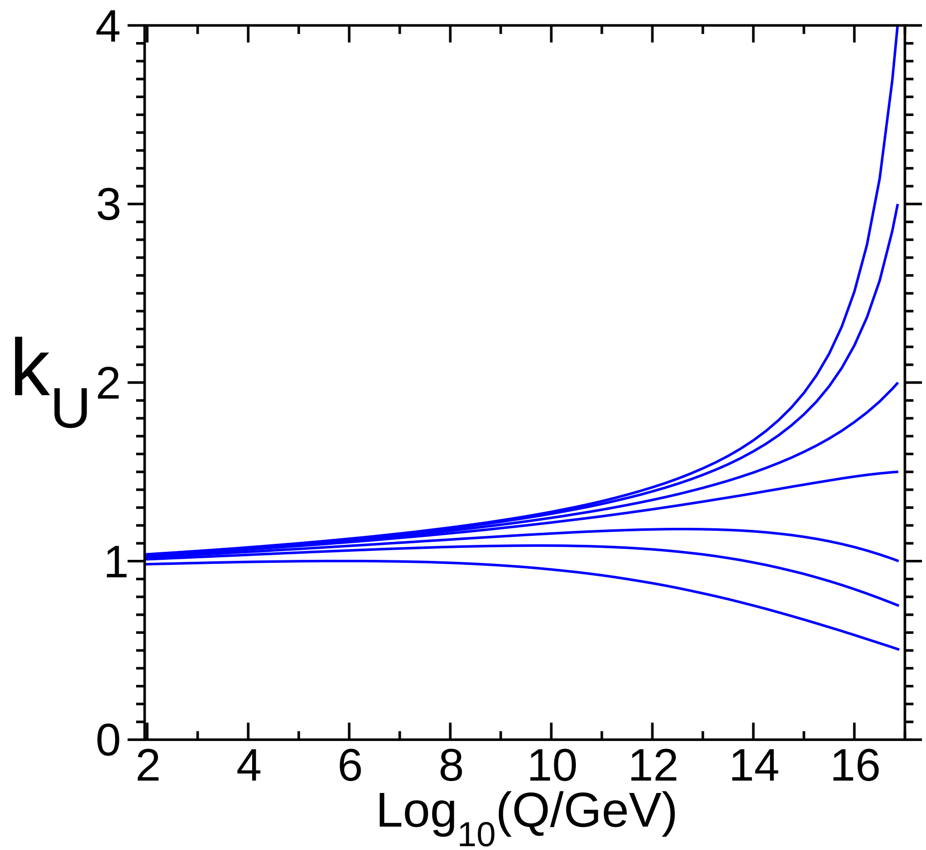
The Yukawa coupling runs at one-loop like:

$$\beta(k) \equiv Q\frac{d}{dQ}k = \frac{1}{16\pi^2}k\left[6k^2 + 3y_t^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right]$$

An infrared-stable fixed point of the Pendleton-Ross-Hill type is reached due to cancellation of positive and negative terms.

Taking into account higher loop order terms, the fixed point is found near $k = 1.05$ in both the QUE and QDEE models.

Infrared-stable fixed point at $k = 1.05$ in the QUE model:



This large value is natural in the sense that many inputs at GUT scale end up there. The QDEE model behaves very similarly.

In QUE Model, the Lagrangian depends on the superpotential:

$$W = M_Q Q\overline{Q} + M_U U\overline{U} + k H_u Q\overline{U} + k' H_d \overline{Q} U$$

and soft SUSY-breaking terms, including:

$$\begin{aligned} -\mathcal{L}_{\text{soft}} &= m_Q^2|Q|^2 + m_{\overline{Q}}^2|\overline{Q}|^2 + m_U^2|U|^2 + m_{\overline{U}}^2|\overline{U}|^2 \\ &\quad + \left(b_Q Q\overline{Q} + b_U U\overline{U} + a_k H_u Q\overline{U} + a_{k'} H_d \overline{Q} U + \text{c.c.}\right) \end{aligned}$$

The charge $\pm 2/3$ fermion mass matrix in the $(Q, U, \overline{Q}, \overline{U})$ basis is (v_u and v_d are the MSSM Higgs VEVs):

$$M_{\text{fermions}} = \begin{pmatrix} 0 & 0 & M_Q & k' v_d \\ 0 & 0 & k v_u & M_U \\ M_Q & k v_u & 0 & 0 \\ k' v_d & M_U & 0 & 0 \end{pmatrix}.$$

In the same basis, the charge $\pm 2/3$ squark (mass)^2 matrix is:

$$M^2_{\rm scalars} = M^2_{\rm fermions} + \begin{pmatrix} m^2_Q & 0 & b_Q & a_{k'} v_d - k'\mu v_u \\ 0 & m^2_U & a_k v_u - k\mu v_d & b_U \\ b_Q & a_k v_u - k\mu v_d & m^2_{\overline{Q}} & 0 \\ a_{k'} v_d - k'\mu v_u & b_U & 0 & m^2_{\overline{U}} \end{pmatrix}.$$

Now one can use the VEV-dependent fermion and scalar squared masses to compute the corrections to the MSSM Higgs mass using the effective potential approximation…

Given the Coleman-Weinberg effective potential contribution V due to the new quarks and squarks, one obtains:

$$\Delta M_h^2 \approx \frac{1}{2}\Big[\sin^2\beta\left(\frac{\partial^2 V}{\partial v_u^2} - \frac{1}{v_u}\frac{\partial V}{\partial v_u}\right) + \cos^2\beta\left(\frac{\partial^2 V}{\partial v_d^2} - \frac{1}{v_d}\frac{\partial V}{\partial v_d}\right) + \sin(2\beta)\frac{\partial^2 V}{\partial v_u \partial v_d}\Big].$$

This can be evaluated numerically for any values of the input parameters.

In the following, I will neglect k', since it doesn't have as big an impact as k on M_h.

For illustration, consider the special limiting case:

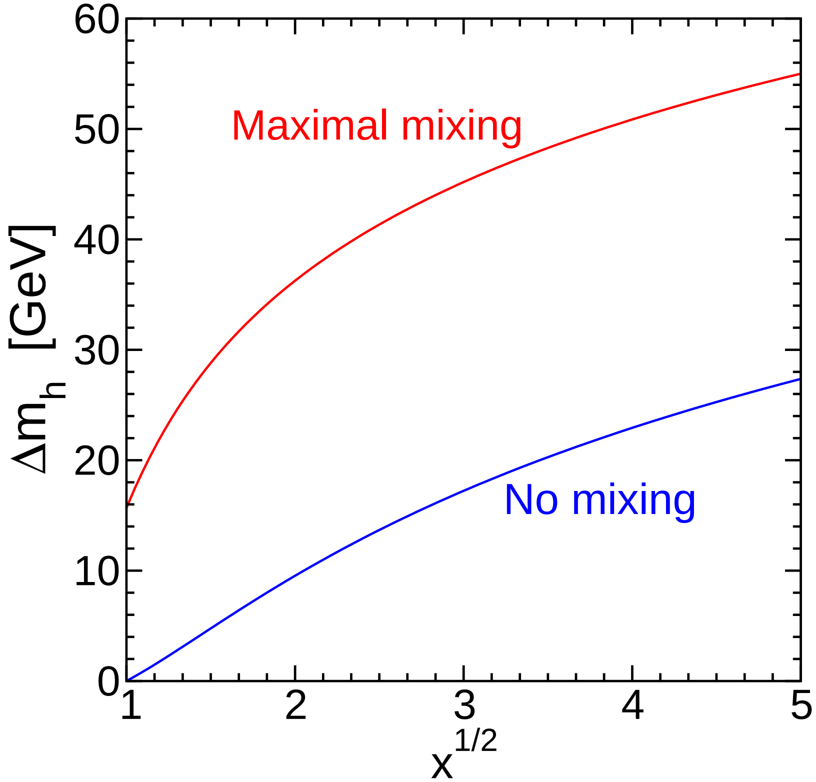
- $M \equiv M_Q = M_U =$ fermion masses,
- $m^2 \equiv m_Q^2 = m_{\overline{Q}}^2 = m_U^2 = m_{\overline{U}}^2 =$ soft scalar mass^2,
- $A \equiv a_k/kM_S =$ soft scalar^3 coupling
- μ, b_Q, b_U, k' and a'_k treated as negligible

Then, expanding in small $kv_u \ll m, M$, one finds (BGRS 2008):

$$\Delta M_h^2 = \frac{3v^2}{4\pi^2}k^4 \sin^4\beta \left[\ln(x) - \frac{5}{6} + \frac{1}{x} - \frac{1}{6x^2} + A^2(1 - \frac{1}{3x}) - \frac{A^4}{12}\right]$$

where $x = M_S/M_F$, with
$M_S = \sqrt{M^2 + m^2} \approx$ average scalar mass, and
M is the average fermion mass.

Estimate of Higgs mass correction in this simple approximation, in either the QUE or QDEE models:



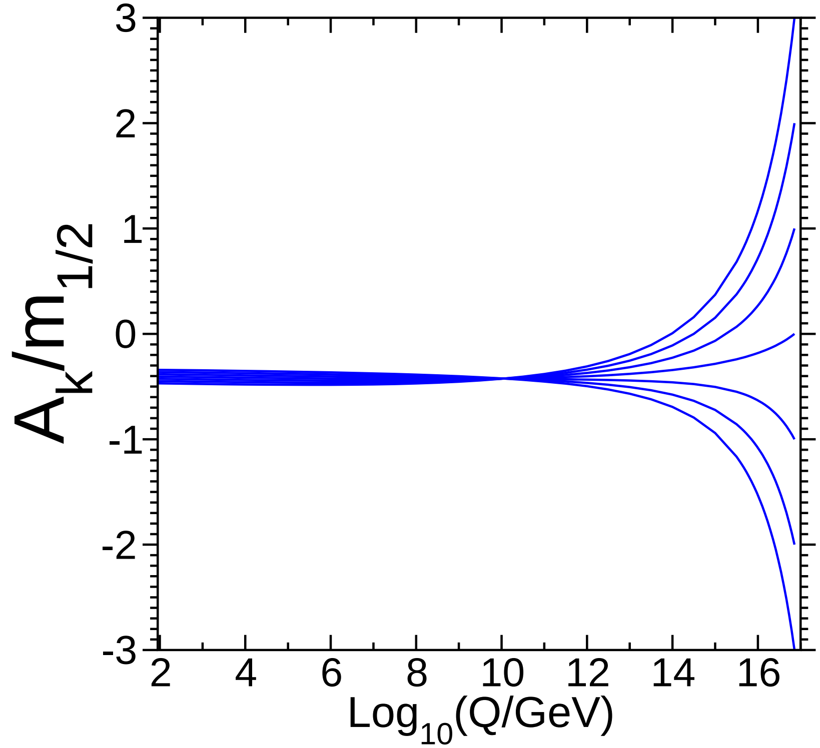
$$x^{1/2} = M_S/M_F$$

No Mixing: $A = 0$

Maximal mixing: $A = 2(1 - 1/3x)$

However, “Maximal mixing” is unlikely because. . .

Near fixed point for k, there is also a strong focusing behavior for A:

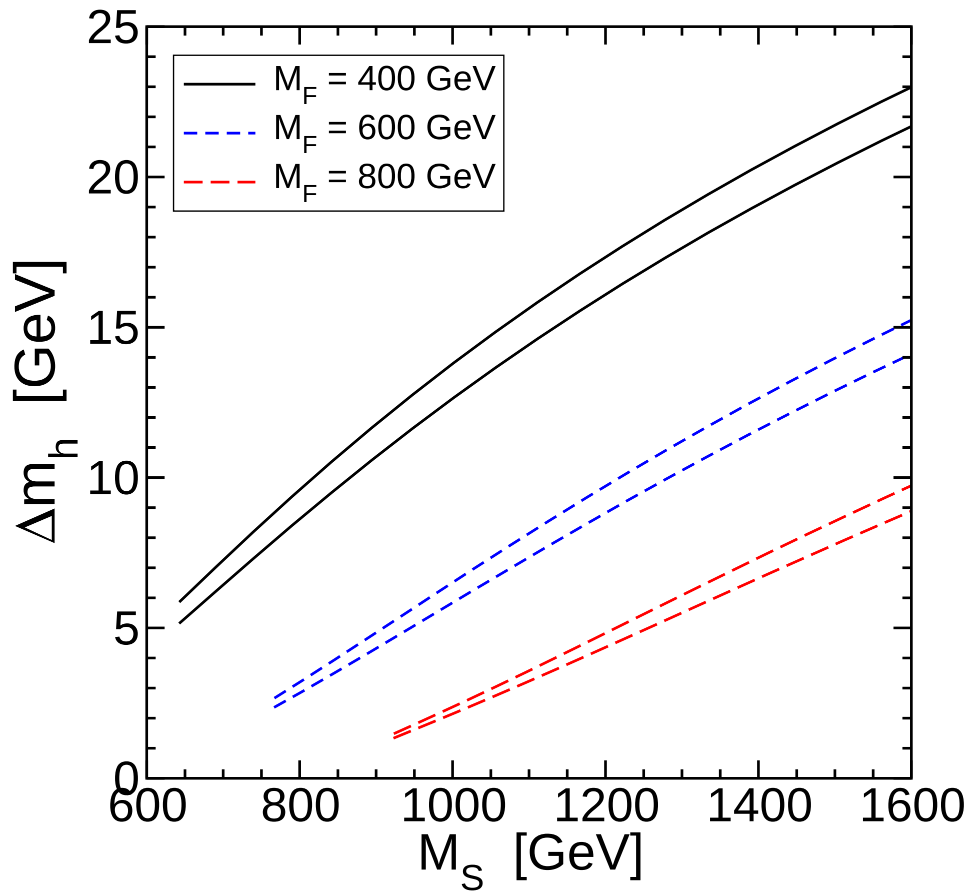


So, for almost every high-scale boundary condition,

$$-0.5 \lesssim A/m_{1/2} \lesssim -0.3,$$

This is much closer to the “No Mixing” scenario than to “Maximal Mixing”.

Higgs mass corrections near the fixed point with $k = 1.05$ in the QUE model, as a function of average scalar mass M_S:



Upper lines: $A = -0.5 m_{1/2}$

Lower lines: $A = -0.3 m_{1/2}$

The most dramatic dependence is on M_S/M_F.

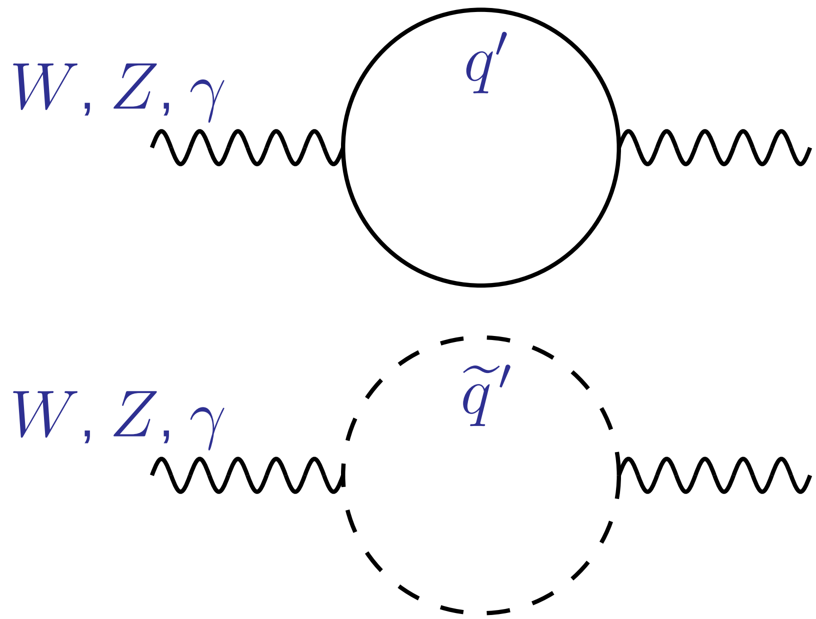
Note that I've assumed fixed point value $k = 1.05$.

The correction ΔM_h^2 scales like k^4.

ΔM_h^2 does NOT decouple with heavy new particles, as long as there is a hierarchy between new scalars and fermions.

Results shown apply for both QUE and QDEE models.
For LND model, ΔM_h^2 is smaller by about a factor of 10, so that model is less appealing.

Since we've added particles charged under $SU(2)_L \times U(1)_Y$ with isospin-violating Yukawa couplings, need to worry about constraints from electroweak observables from W, Z, γ self-energy corrections:



Use Peskin-Takeuchi S, T to parameterize deviations from Standard Model.

Corrections to Peskin-Takeuchi S, T parameters are approximately:

$$\Delta T \approx \frac{13 N_c}{480 \pi s_W^2 m_W^2 M_F^2} k^4 \sin^4\beta \approx 0.10 k^4 \sin^4\beta \left(\frac{400 \text{ GeV}}{M_F}\right)^2$$

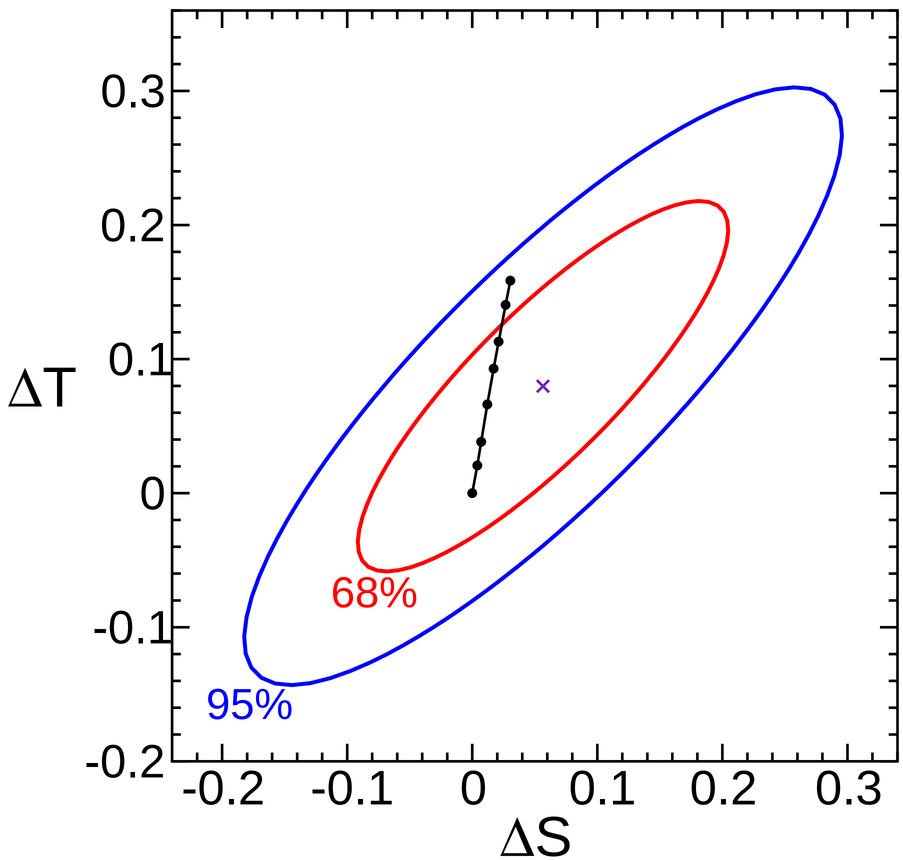
$$\Delta S \approx \frac{2 N_c}{15 \pi M_F^2} k^2 \sin^2\beta \approx 0.024 k^2 \sin^2\beta \left(\frac{400 \text{ GeV}}{M_F}\right)^2$$

The scalar sector contributes a smaller but non-negligible amount.

The contributions from the usual MSSM sparticles are also smaller but non-negligible.

Note that these corrections do decouple quadratically with M_F, unlike the Higgs mass corrections.

For a better estimate, consider typical QUE models with varying $M \equiv M_Q = M_U$. Scalar contributions use $m_{1/2} = 600$ GeV.



$\Delta S = \Delta T = 0$ defined here by Standard Model with $m_t = 173.1$ GeV, $M_h = 115$ GeV.

$\times$ = best fit to Z-pole data.

Black dots are $m_{t'_1} = 275, 300, 350, 400, 500, 700, 1000$ GeV and ∞.

New particles (besides the usual MSSM) in **QUE Model**:

Fermions		Scalars	
$t',\ t''$	(charge $+2/3$)	$\tilde{t}'_i$	($i = 1, 2, 3, 4$)
b'	(charge $-1/3$)	$\tilde{b}'_i$	($i = 1, 2$)
τ'	(charge -1)	$\tilde{\tau}'_i$	($i = 1, 2$)

In **QDEE Model**:

Fermions		Scalars	
$b',\ b''$	(charge $-1/3$)	$\tilde{b}'_i$	($i = 1, 2, 3, 4$)
t'	(charge $2/3$)	$\tilde{t}'_i$	($i = 1, 2$)
$\tau',\ \tau''$	(charge -1)	$\tilde{\tau}'_i$	($i = 1, 2, 3, 4$)

Due to soft SUSY breaking, the extra scalars will be heavier than their fermion partners. All new particles should be $\lesssim 1$ TeV.

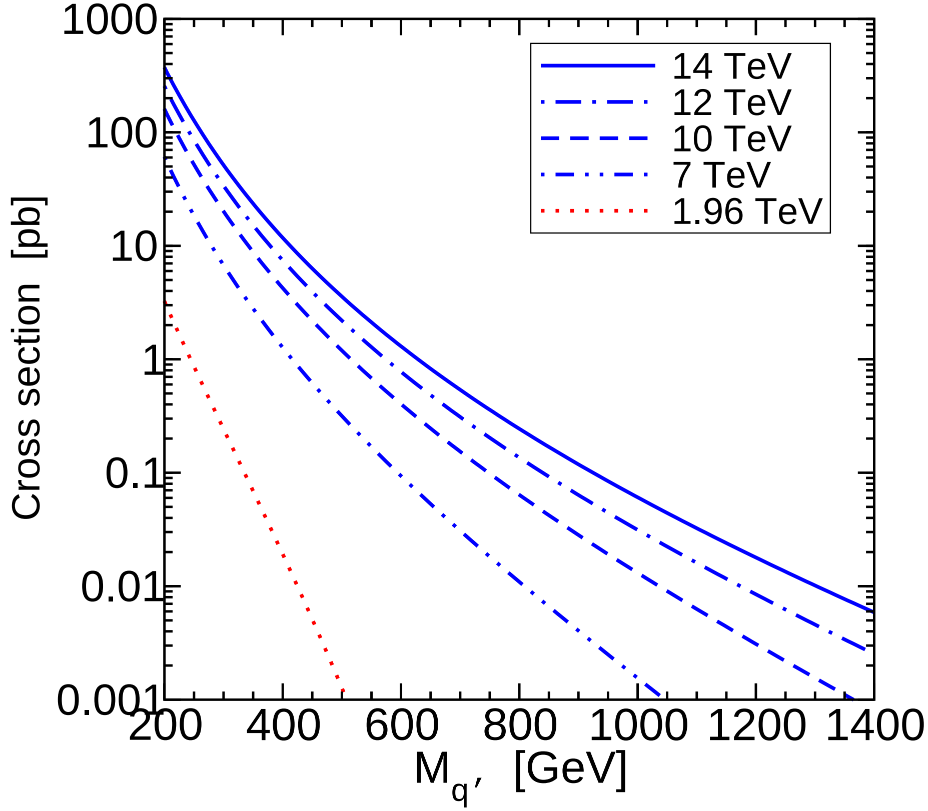
General comments on collider phenomenology:

- Largest production cross-section involves the lightest new strongly-interacting fermion: always t' for QUE Model and b' for QDEE Model.
- New extra particles and sparticles probably won't appear in cascade decay of MSSM superpartners (notably the gluino), due to kinematic prohibition or suppression.
- Lightest new fermions can only decay by mixing with Standard Model fermions. If this is very small, the lightest new fermions could be long-lived on collider scales, yielding charged massive particles or displaced vertices.
- Mixing with Standard Model fermions is highly constrained (no GIM mechanism) except for the third family, so decays to t, b are most likely case.

Limits from Tevatron (CDF)

- $m_{t'} > 311$ GeV if BR($t' \rightarrow Wq$) is 100%.
  Based on lepton + jets + $E_T^{\rm miss}$ search with 2.8 fb^{-1}.
- $m_{b'} > 325$ GeV if BR($b' \rightarrow Wt$) is 100%.
  Based on same-charge dilepton search with 2.7 fb^{-1}.
- $m_{b'} > 268$ GeV if BR($b' \rightarrow Zb$) is 100%.
  Based on 1.06 fb^{-1}.
- $m_{b'} > 295$ GeV if BR($b' \rightarrow Wt, Zb, hb$) = ($0.5$, 0.25, 0.25).
  Based on dilepton search with 1.2 fb^{-1}.
- $m_{q'} \gtrsim 350$ GeV if q' long-lived
  Based on time-of-flight measurement with 1.06 fb^{-1}.

New quark-antiquark production at hadron colliders:



How does the t' decay in QUE Model?

Depends on the form of the mixing term between the extra quarks and the Standard Model ones (assumed to be t, b). Possible terms are:

- $\mathcal{L} = H_d Q \bar{b}$

  This implies dominantly charged-current ("W-philic") decays, with $BR(t' \to bW, tZ, hZ) = (1, 0, 0)$ in the high mass limit.

- $\mathcal{L} = H_u Q \bar{t}$

  This implies dominantly neutral current ("W-phobic") decays, with $BR(t' \to bW, tZ, hZ) = (0, 0.5, 0.5)$ in the high mass limit.

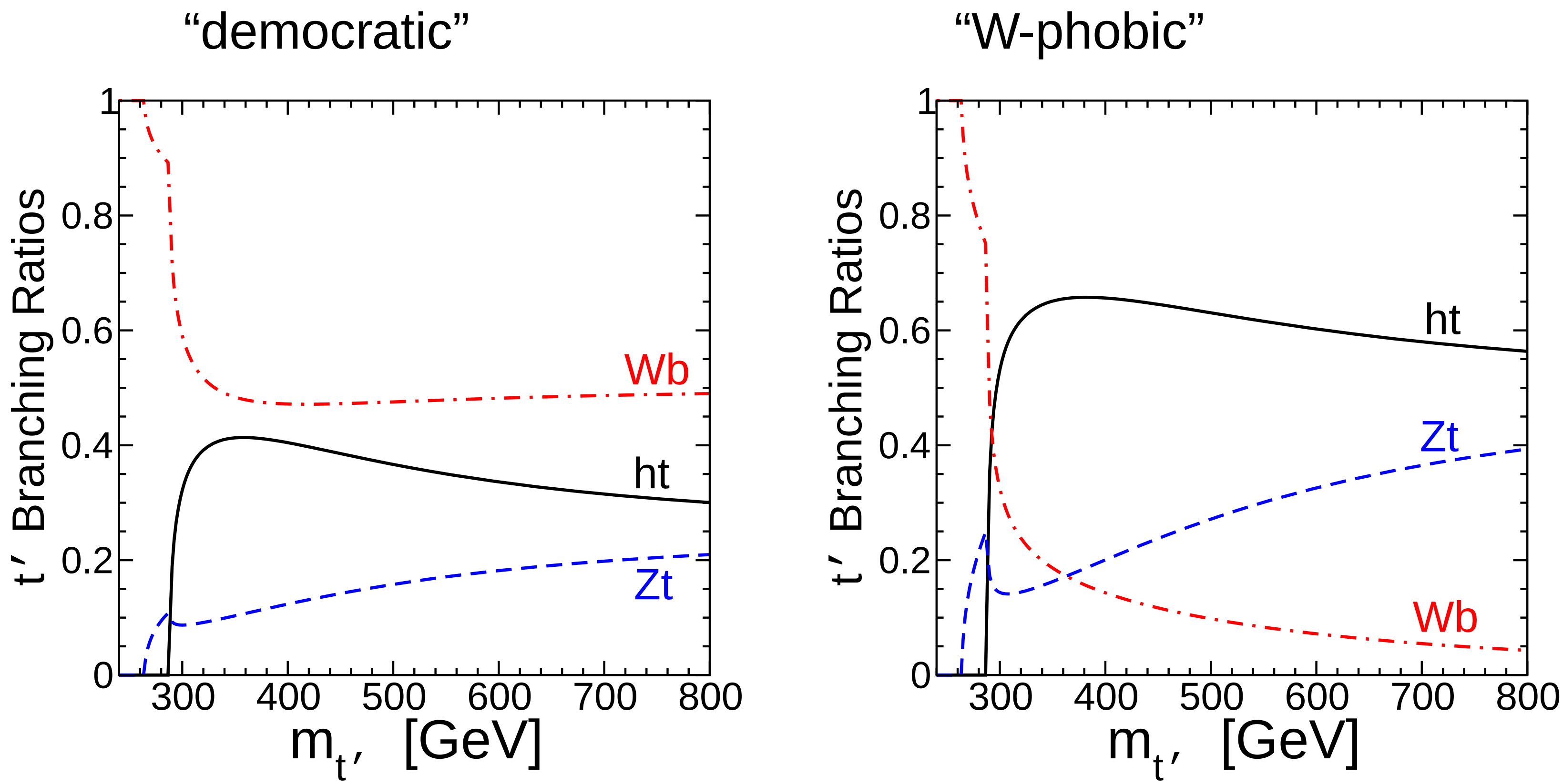
- $\mathcal{L} = H_u \begin{pmatrix} t \\ b \end{pmatrix} \overline{U}$

  This implies "democratic" decays, with $BR(t' \to bW, tZ, hZ) = (0.5, 0.25, 0.25)$ in the high mass limit.

Linear combinations of these are also possible.

Mass effects are important in “W-phobic” and “democratic” cases.

t' Branching ratios in QUE model:



Note Tevatron search assumes large BR$(t' \to Wq)$, but this is **not** necessarily valid.

LHC signals depend crucially on the mixing of the new quarks with the Standard Model ones.

For example, what if the W decays dominate?

In the QUE Model, the t' signature is the same as for ordinary t, but with a larger mass:

$$pp \to t'\overline{t'} \to W^+ b W^- \overline{b}.$$

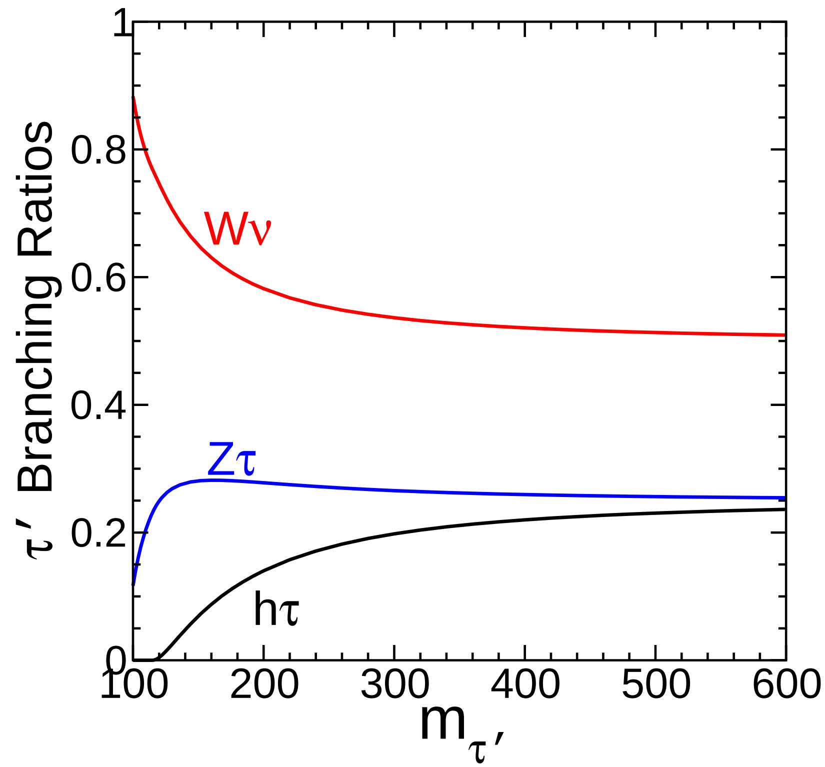
In the QDEE Model, there could be a same-sign dilepton signal from

$$pp \to b'\overline{b'} \to W^- t W^+ \overline{t} \to W^+ W^+ W^- W^- b\overline{b} \to \ell^+\ell^+ bbjjjj + E_T^{\rm miss}$$

(This is also a plain MSSM signature in many scenarios.)

In both cases, the signals will be made more “interesting” from both SUSY backgrounds and cascade decays from the heavier fermions.

In both QUE and QDEE Models, gauge coupling unification demands a τ' whose branching ratios depend only on its mass:



For large $m_{\tau'}$, the Goldstone equivalence theorem implies

$$\text{BR}(W\nu) : \text{BR}(Z\tau) : \text{BR}(h\tau) = 2 : 1 : 1.$$

Can Tevatron place any bound on such a τ' ?

Conclusion

Models with extra vector-like chiral supermultiplets:

- With a new Yukawa coupling at its fixed point, naturally raise the h^0 mass, help explain why not seen at LEP2
- Preserve perturbative gauge coupling unification
- Fine with precision electroweak constraints if $m_{t'}, m_{b'} \gtrsim$ 300 GeV, maybe even lighter.
- Tevatron limits are not much stronger (so far)
- Should be decisively confronted at full-strength LHC