Supersymmetry with extra vector-like matter

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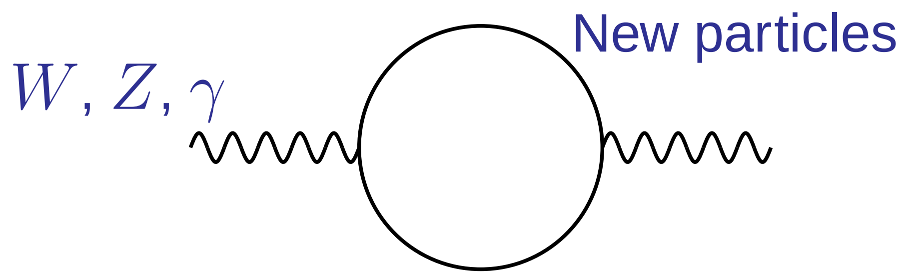
Based on `0910.2732` and `1006.4186` and `1009.????`.

Precision electroweak observables severely limit new physics beyond the Standard Model:



Constraints mostly captured by Peskin-Takeuchi S, T parameters.

Impact of supersymmetric particles is moderate.

Another case with naturally small corrections: “vector-like” matter.

It is natural to combine these!

Vector-like matter = new fields in real representations of unbroken gauge group.

Fermion masses are bare, independent of electroweak breaking:

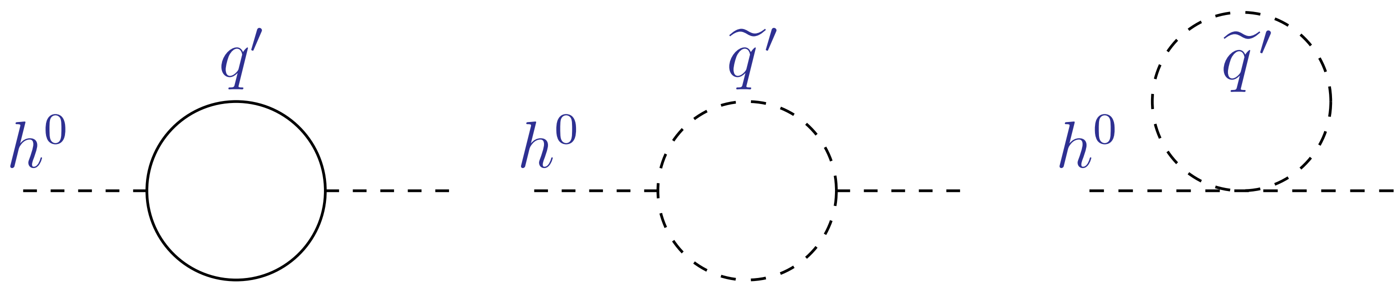
$$\mathcal{L} = -M\Psi\Psi.$$

Can still also have Yukawa couplings to Higgs boson = subdominant contribution to mass.

Corrections to S, T decouple like $1/M^2$.

LEP2 limit in the decoupling case: $m_{h^0} > 114$ GeV.

Vector-like supermultiplets can raise $m^2_{h^0}$ through their Yukawa couplings:



These contributions do **not** decouple for large $M_{q'}$, as long as there is a significant ratio $M_{\tilde{q}'}/M_{q'} > 1$.

However, one must be careful: this does not necessarily help the SUSY little hierarchy problem, because the new particles *also* raise $|\mu|$ through renormalization group running effects.

Generic structure of new extra vector-like matter superfields:

$$\Phi, \overline{\Phi} \quad = \quad SU(2)_L \text{ doublets (vector-like)}$$
$$\phi, \overline{\phi} \quad = \quad SU(2)_L \text{ singlets (vector-like)}$$

Superpotential:

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

Yukawa coupling = k, and $\Delta m^2_{h^0} \propto k^4 v^2$.

So want k as large as possible = IR quasi-fixed point of renormalization group equations.

Important earlier work on this subject:

Moroi and Okada 1992,

Babu, Gogoladze, and Kolda 2004,

Babu, Gogoladze, Rehman, Shafi 2008.

Corrections to the Peskin-Takeuchi T parameter had been overestimated by a factor of about 4. So much less constrained than previously thought!

Want to maintain or improve successes of minimal SUSY:

- Perturbative gauge coupling unification
- No unconfined fractional charges
- Avoid fine tuning: new particles not too heavy.

Building block superfields, under $SU(3)_C \times SU(2)_L \times U(1)_Y$:

$$Q, \overline{Q}: \quad (\mathbf{3}, \mathbf{2}, \frac{1}{6}), \ (\overline{\mathbf{3}}, \mathbf{2}, -\frac{1}{6})$$

$$U, \overline{U}: \quad (\mathbf{3}, \mathbf{1}, \frac{2}{3}), \ (\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$$

$$D, \overline{D}: \quad (\mathbf{3}, \mathbf{1}, -\frac{1}{3}), \ (\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$$

$$L, \overline{L}: \quad (\mathbf{1}, \mathbf{2}, -\frac{1}{2}), \ (\mathbf{1}, \mathbf{2}, \frac{1}{2})$$

$$E, \overline{E}: \quad (\mathbf{1}, \mathbf{1}, -1), \ (\mathbf{1}, \mathbf{1}, 1)$$

$$N: \quad (\mathbf{1}, \mathbf{1}, 0)$$ (singlet)

$$T: \quad (\mathbf{1}, \mathbf{3}, 0)$$ (electroweak triplet)

$$O: \quad (\mathbf{8}, \mathbf{1}, 0)$$ (color octet))

All others give unconfined fractional charges, or will ruin perturbative unification.

Models with perturbative unification:

(LND)^n : $(L, \overline{L}, D, \overline{D}, N, \overline{N}) \times n$ [$\mathbf{5} + \overline{\mathbf{5}}$ of $SU(5)$, $n = 1, 2, 3$]

QUE : $Q, \overline{Q}, U, \overline{U}, E, \overline{E}$ [$\mathbf{10} + \overline{\mathbf{10}}$ of $SU(5)$]

QDEE : $Q, \overline{Q}, D, \overline{D}, E, \overline{E}, E, \overline{E}$

OTLEE : $O, T, L, \overline{L}, E, \overline{E}, E, \overline{E}$ [adjoint of $SU(3)_c \times SU(3)_L \times SU(3)_R$]

$\ldots$

(There are 5 more.)

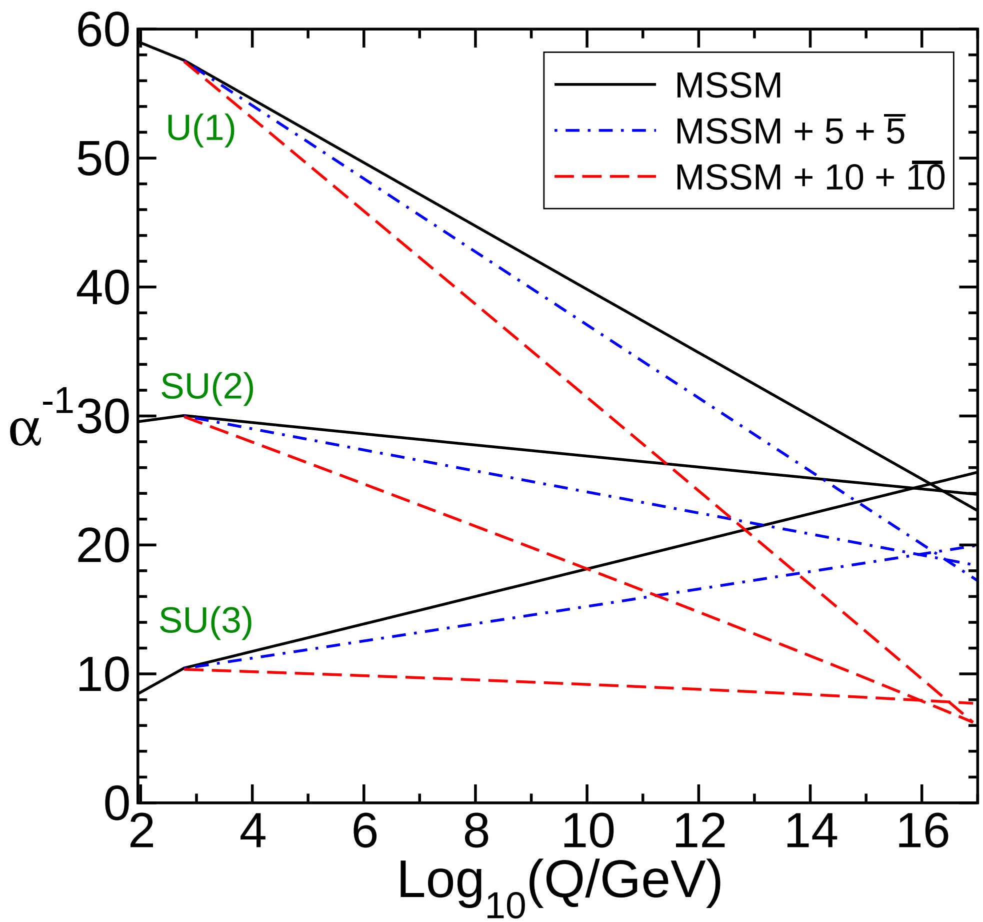
The OTLEE model has a qualitatively different feature than first three:

$\mathcal{L} = kH_u TL =$ (Higgs doublet)(triplet)(doublet) Yukawa coupling

See 1006.4186 (SPM) for more details.

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

Three-loop running:



Black = MSSM

Blue = LND Model

Red = QUE Model

(QDEE, OTLEE similar)

All new particle

thresholds taken

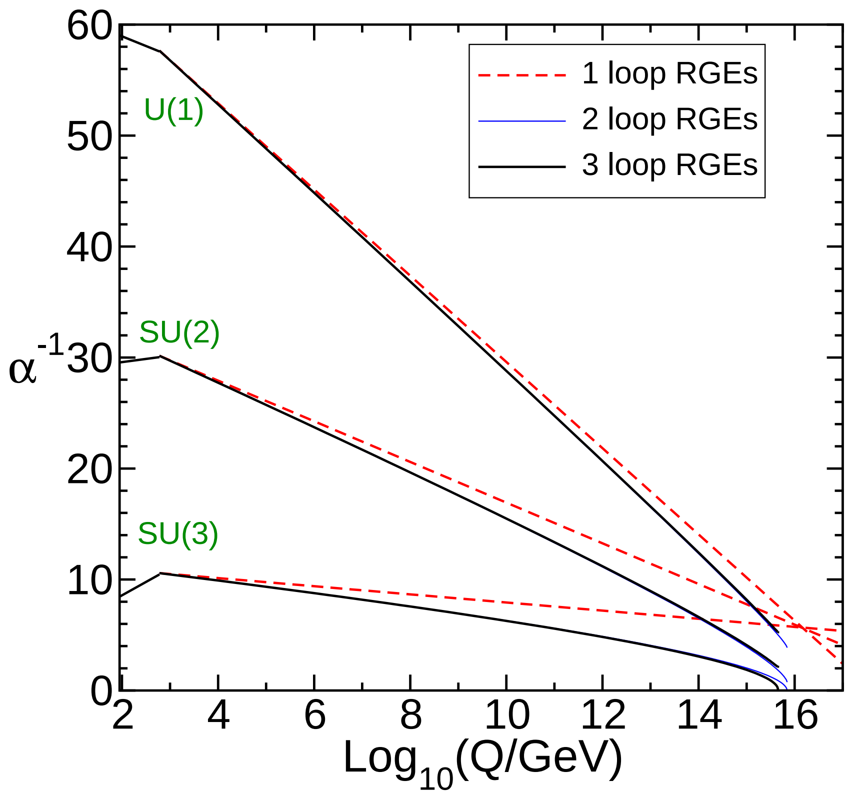
at $Q = 600$ GeV.

Extra fields contribute equally to the three beta functions at 1 loop.

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

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

However, taking into account higher-loop effects, perturbative unification fails (unless new particle masses $\gtrsim$ 2.5 TeV):



QUE Model:

$$W = M_Q Q\overline{Q} + M_U U\overline{U} + kH_u Q\overline{U} + M_E E\overline{E}$$

The Yukawa coupling k has an IR quasi-fixed point at $k \approx 1.05$.

New fermions: $t', \quad t'', \quad b', \quad \tau'$

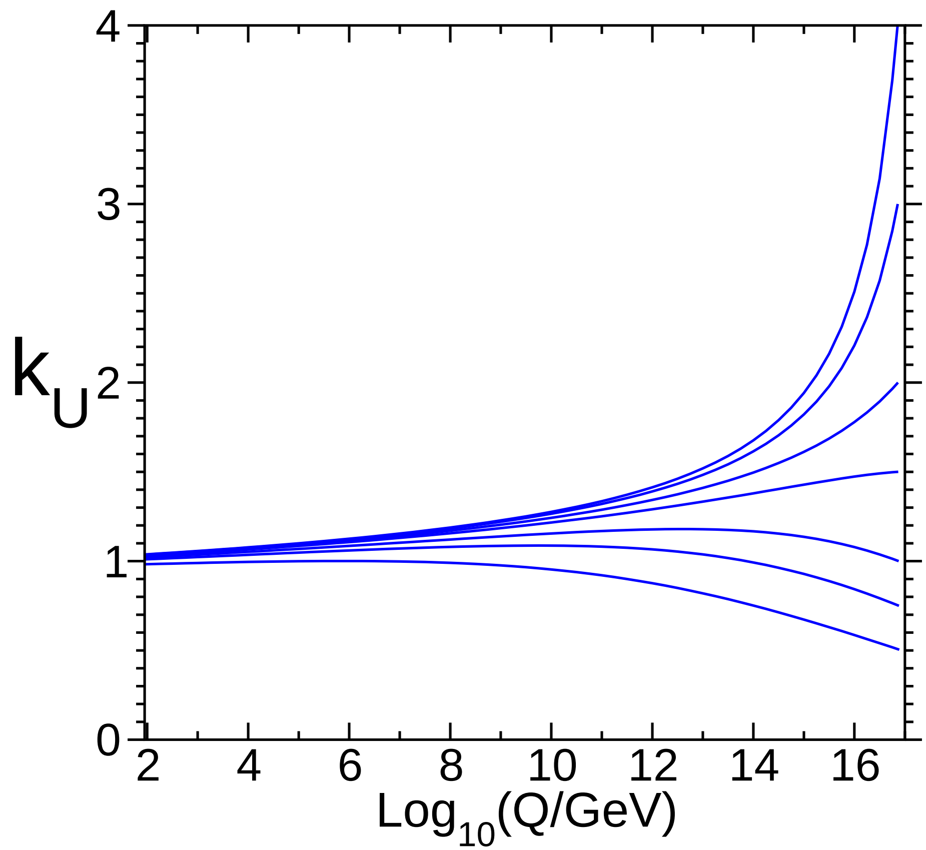
New scalars: $\tilde{t}'_{1,2,3,4}, \quad \tilde{b}'_{1,2}, \quad \tilde{\tau}'_{1,2}$

Soft susy-breaking Lagrangian:

$$-\mathcal{L}_{\rm soft} = a_k H_u Q\overline{U} + m_Q^2|Q|^2 + \ldots$$

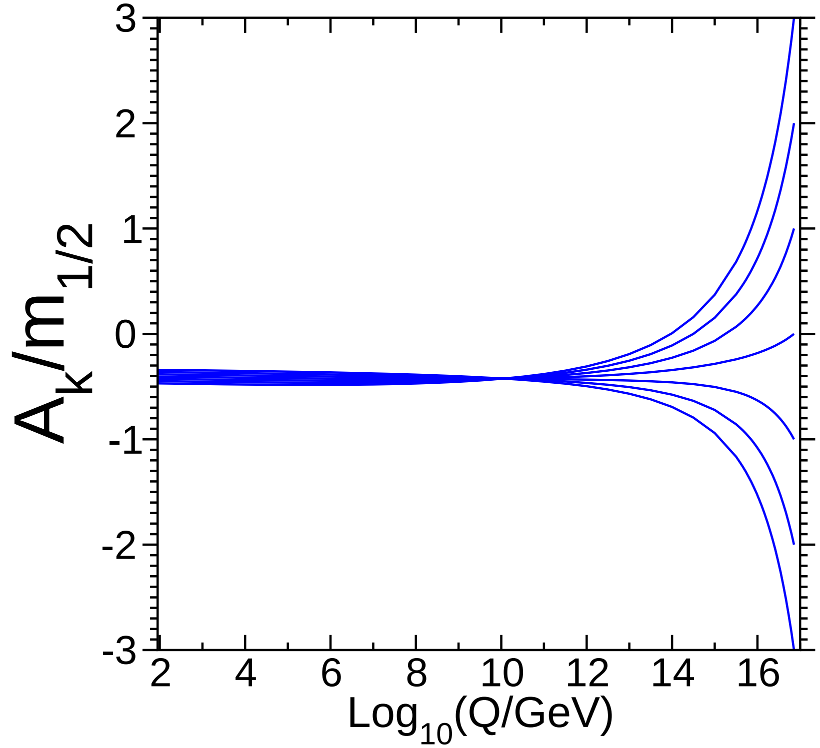
The corrections to Δm_h^2 depend strongly on a_k, which also has a strongly attractive fixed point.

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.

Near fixed point for k, there is also a strong focusing behavior for $A_k = a_k/k$:

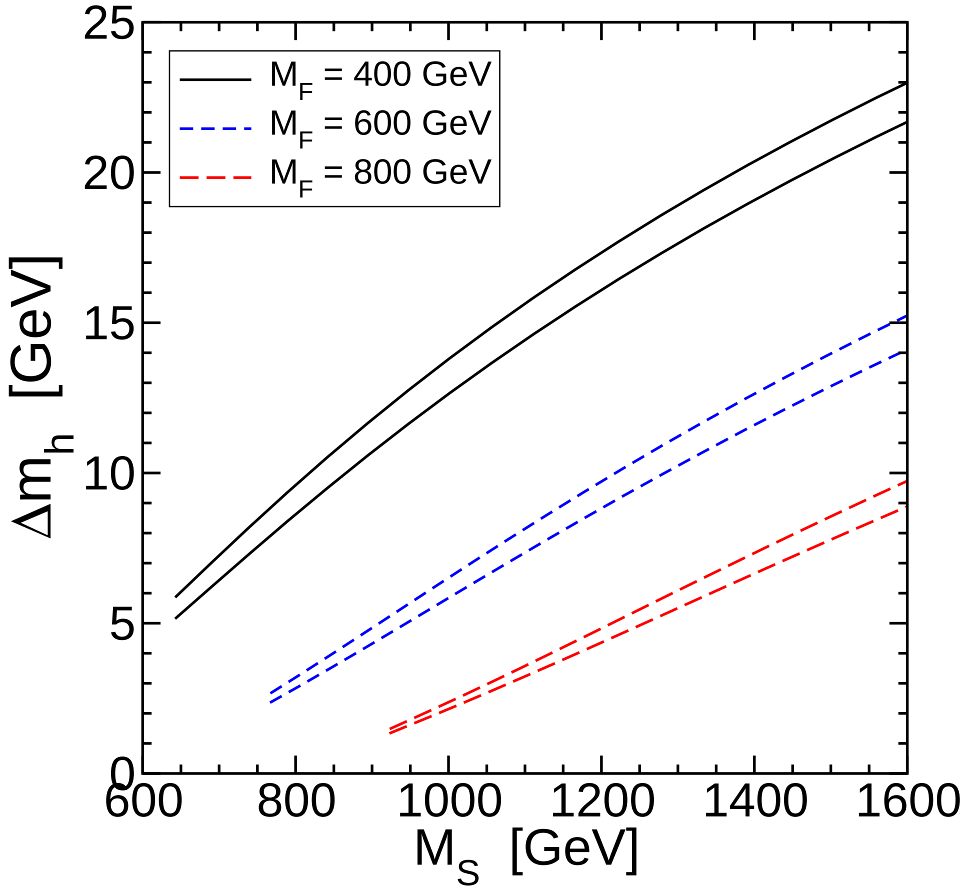


For almost every high-scale boundary condition,

$$-0.5 \lesssim A_k/m_{1/2} \lesssim -0.3.$$

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:

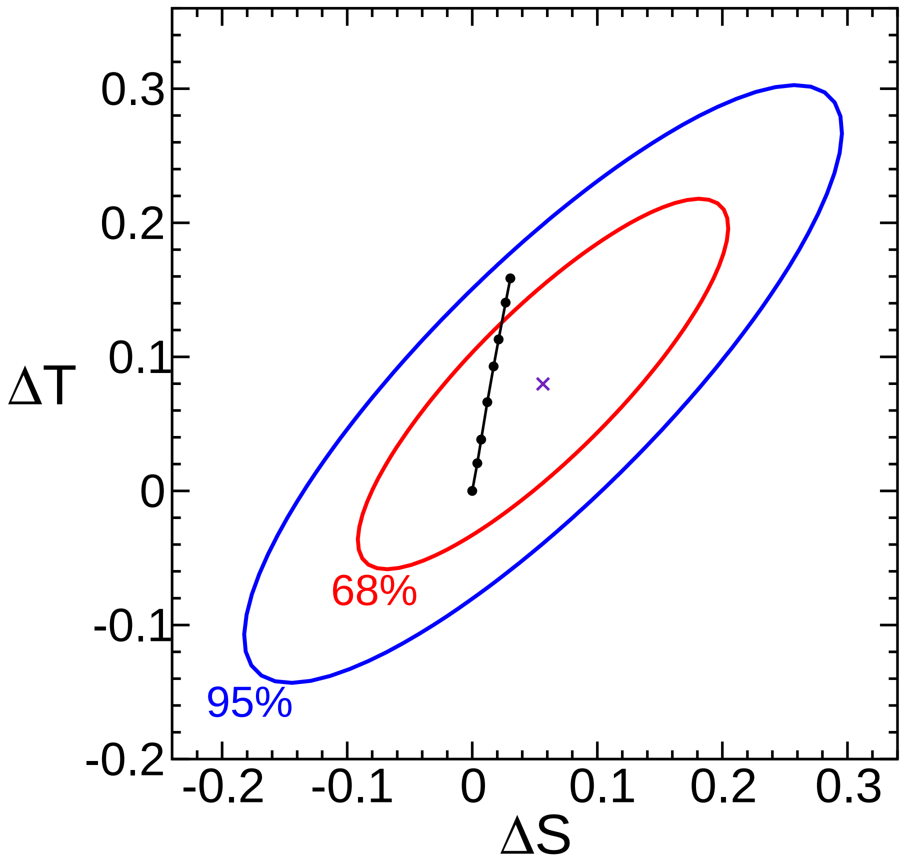


Upper lines: $A_k = -0.5m_{1/2}$

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

The most dramatic dependence is on M_S/M_F.

ΔS, ΔT for typical QUE model with varying $M \equiv M_Q = M_U$ and $m_{1/2} = 600$ 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 ∞.

General comments on collider phenomenology:

- Largest production cross-section involves the lightest new quark: 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)

- $m_{t'} > 335$ GeV if BR($t' \to Wq$) is 100%.

  Based on lepton + jets + $E_T^{\rm miss}$ search with 4.6 fb^{-1}.

  CDF note 10110. (Slight excess. Expected limit was $m_{t'} > 372$ GeV.)

- $m_{b'} > 338$ GeV if BR($b' \to Wt$) is 100%.

  Based on same-charge dilepton search with 2.7 fb^{-1}.

- $m_{b'} > 268$ GeV if BR($b' \to Zb$) is 100%.

  Based on 1.06 fb^{-1}.

- $m_{b'} > 295$ GeV if BR($b' \to Wt, Zb, hb$) = $(0.5, 0.25, 0.25)$.

  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}.

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:

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

  Implies charged-current (“W-philic”) decays, with

  $BR(t' \to bW,\, tZ,\, th) = (1, 0, 0)$.

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

  Implies dominantly neutral current (“W-phobic”) decays, with

  $BR(t' \to bW,\, tZ,\, th) = (0, 0.5, 0.5)$ in the high mass limit.

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

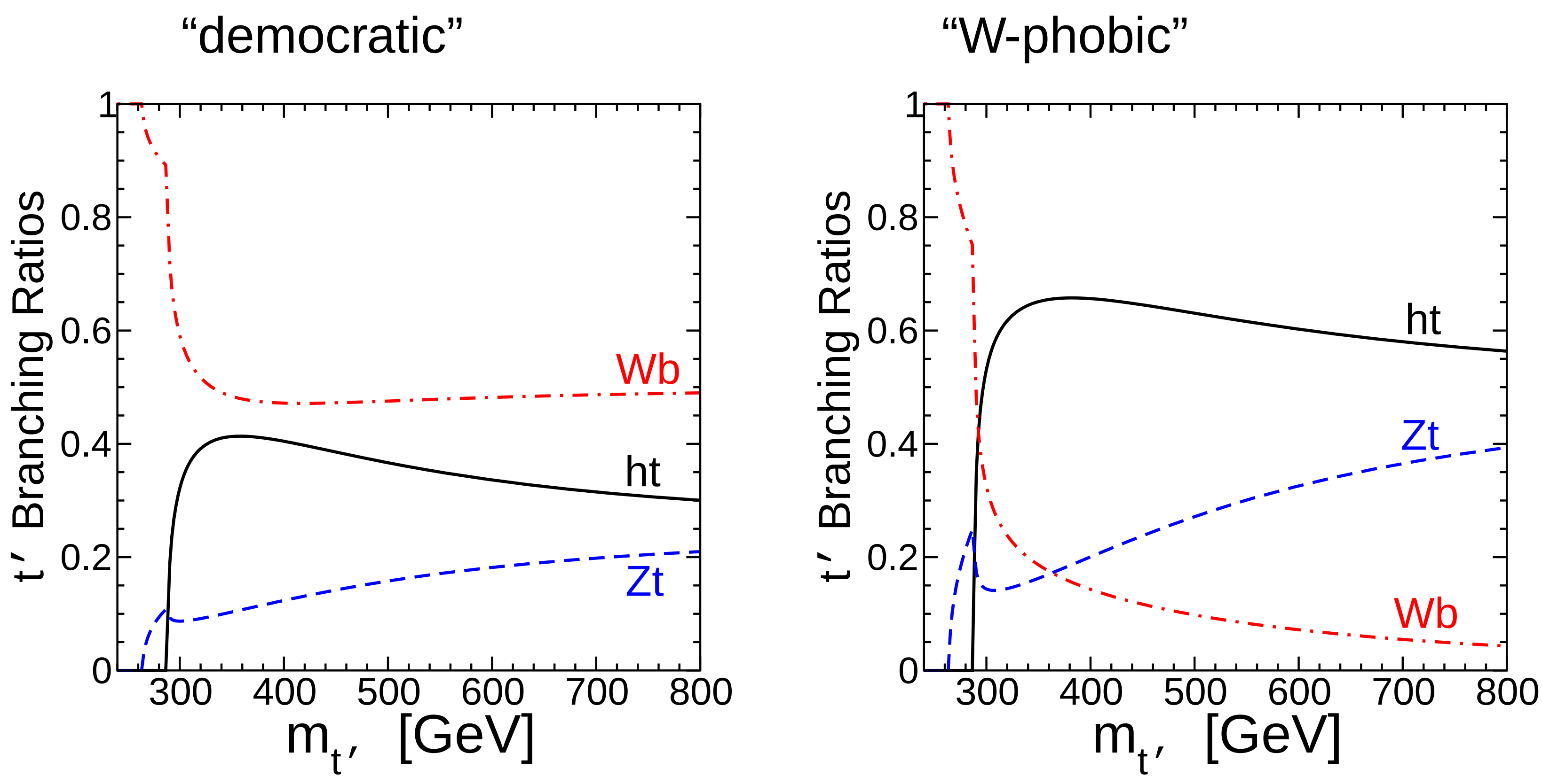
  Implies “democratic” decays, with

  $BR(t' \to bW,\, tZ,\, th) = (0.5, 0.25, 0.25)$ 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 CDF search assumes large BR$(t' \to Wq)$, but this is not inevitable.

LHC signals depend on the mixing of the new quarks with the Standard Model ones. For example, if the W decays dominate:

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

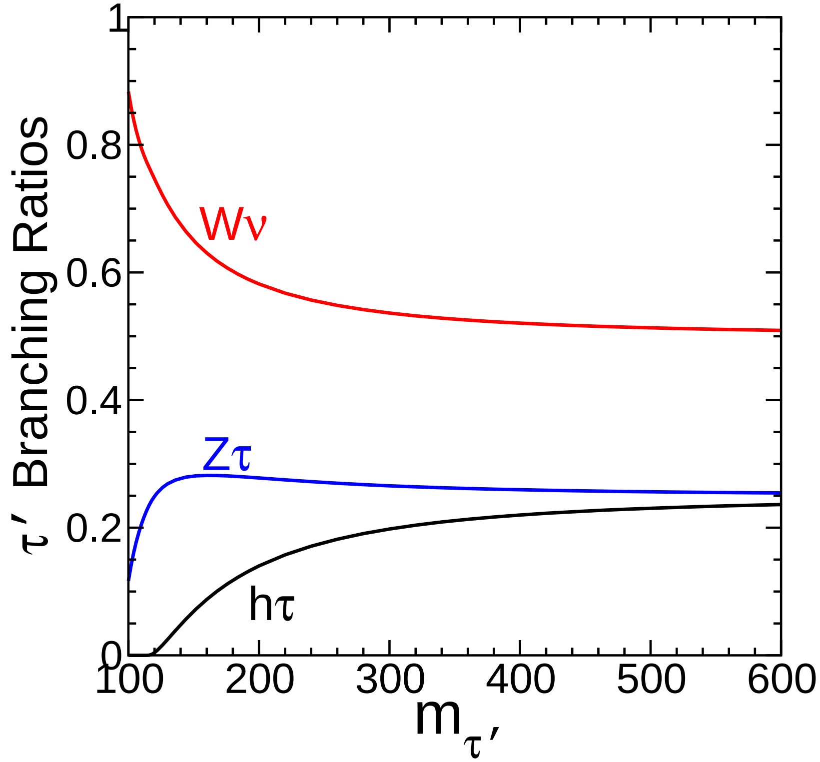
$$pp \to t'\overline{t'} \to W^+ b W^- \bar{b}.$$

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

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

Many more possibilities!

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' ? What about LHC?

Quirky Supersymmetry with gauge coupling unification

What if $L, \overline{L}, D, \overline{D}, N, \overline{N}$ transform under a new, unbroken, confining gauge symmetry G_X ? (Babu, Gogoladze, Kolda 2004.)

Phenomenology is “quirky”. (Kang+Luty 2008, see also Okun 1980, Strassler+Zurek 2006)

When pair-produced, the quirks $L, \overline{L}, D, \overline{D}, N, \overline{N}$ are connected by stable flux strings of length $L \approx (\Delta E)/\Lambda^2$, where ΔE is the kinetic energy of the hard production process, and Λ is the confinement scale for G_X. The string length L can be macroscopic if $\Lambda \lesssim$ keV.

Quirkonium flux strings do not break like in QCD, provided that the quirk masses are larger than Λ.

Three types of models preserve *perturbative* gauge unification of $G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$:

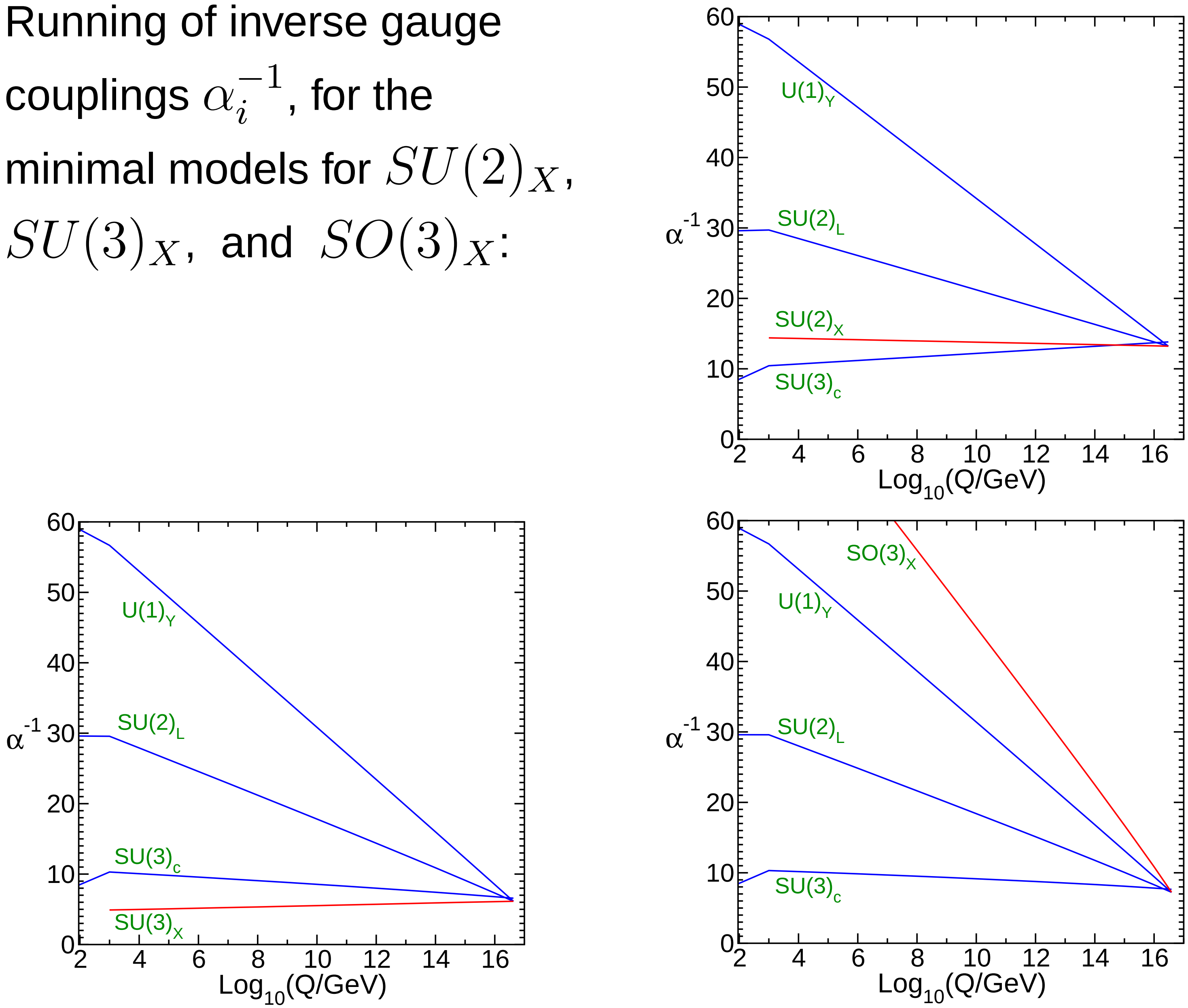
$$\mathbf{SU(2)_X \times G_{SM}}: \quad \begin{aligned} D, \overline{D} &= (\mathbf{2}, \mathbf{3}, \mathbf{1}, -\tfrac{1}{3}) + (\mathbf{2}, \overline{\mathbf{3}}, \mathbf{1}, \tfrac{1}{3}) \\ \overline{L}, L &= (\mathbf{2}, \mathbf{1}, \mathbf{2}, \tfrac{1}{2}) + (\mathbf{2}, \mathbf{1}, \mathbf{2}, -\tfrac{1}{2}) \\ N, \overline{N} &= (\mathbf{2}, \mathbf{1}, \mathbf{1}, 0) \times 2n, \end{aligned}$$

$$\mathbf{SU(3)_X \times G_{SM}}: \quad \begin{aligned} D, \overline{D} &= (\mathbf{3}, \mathbf{3}, \mathbf{1}, -\tfrac{1}{3}) + (\overline{\mathbf{3}}, \overline{\mathbf{3}}, \mathbf{1}, \tfrac{1}{3}) \\ \overline{L}, L &= (\mathbf{3}, \mathbf{1}, \mathbf{2}, \tfrac{1}{2}) + (\overline{\mathbf{3}}, \mathbf{1}, \mathbf{2}, -\tfrac{1}{2}) \\ N, \overline{N} &= [(\mathbf{3}, \mathbf{1}, \mathbf{1}, 0) + (\overline{\mathbf{3}}, \mathbf{1}, \mathbf{1}, 0)] \times n, \end{aligned}$$

$$\mathbf{SO(3)_X \times G_{SM}}: \quad \begin{aligned} D, \overline{D} &= (\mathbf{3}, \mathbf{3}, \mathbf{1}, -\tfrac{1}{3}) + (\mathbf{3}, \overline{\mathbf{3}}, \mathbf{1}, \tfrac{1}{3}) \\ \overline{L}, L &= (\mathbf{3}, \mathbf{1}, \mathbf{2}, \tfrac{1}{2}) + (\mathbf{3}, \mathbf{1}, \mathbf{2}, -\tfrac{1}{2}) \\ N, \overline{N} &= (\mathbf{3}, \mathbf{1}, \mathbf{1}, 0) \times n, \end{aligned}$$

If g_X unifies with the MSSM gauge couplings at $M_{\rm GUT} = 2.5 \times 10^{16}$ GeV, one finds very different behavior for the minimal versions of these models:

Running of inverse gauge couplings α_i^{-1}, for the minimal models for $SU(2)_X$, $SU(3)_X$, and $SO(3)_X$:



Minimal models, taking unification seriously

Confinement scale in terms of $M_{\rm T}$ = effective decoupling scale for new particles:

For $SU(2)_X$ with $n = 0$:

$$\Lambda \approx 1.1\,\mathrm{GeV}\left(\frac{M_{\rm T}}{\mathrm{TeV}}\right)$$

Microscopically confined quirkonium decays promptly, as in Kang+Luty; can give "hadronic fireballs" with hundreds of soft pions.

For $SU(3)_X$ with $n = 3$:

$$\Lambda \approx 120\,\mathrm{GeV}\left(\frac{M_{\rm T}}{\mathrm{TeV}}\right)$$

Quirkonium decay to G_X-glueballs is kinematically inhibited or prohibited by large glueball mass $m_{0^{++}} = 6.7\Lambda$.

For $SO(3)_X$ with $n = 0$:

$$\Lambda \approx 10^{-18}\,\mathrm{eV}\left(\frac{M_\mathrm{T}}{\mathrm{TeV}}\right)$$

Confinement length is of order 10^{11} meters, or roughly the size of the Earth's orbit around the Sun! The new fermions behave as if free, even though technically "confined".

Quirks in these models can decay and annihilate in interesting ways.

In non-minimal versions of the models (with extra G_{SM}-singlets transforming non-trivially under G_X), can get macroscopic flux strings as in Kang+Luty.

For more, see upcoming preprint.

Conclusion

Models with extra vector-like chiral supermultiplets:

- Preserve perturbative gauge coupling unification
- With a new Yukawa coupling at its fixed point, naturally raise the h^0 mass, help explain why not seen at LEP2
- Precision electroweak constraints decouple, are fine if $m_{t'}, m_{b'} \gtrsim$ 300 GeV, maybe even lighter.
- Tevatron limits are not much stronger (so far)
  - Can Tevatron put a limit on $t' \to Zt$ or $t' \to ht$?
  - Can Tevatron put a limit on τ' ?
- Should be decisively confronted at full-strength LHC
- Quirky SUSY presents interesting challenges for colliders.