A Fourth Chiral Generation and SUSY Breaking

Akın Wingerter

Laboratoire de Physique Subatomique et de Cosmologie, Grenoble

March 15, 2011

Talk based on *JHEP* 03 (2010) 023 (arXiv:0911.1882)

In Collaboration with Rohini M. Godbole and Sudhir K. Vempati

A Fourth Generation of Fermions?

- Interest in a 4th generation of fermions has waxed and waned
- No reason why there should not be a 4th generation
- **Particle Data Group** Collaboration, C. Amsler *et al.*,*Phys. Lett.* **B667** (2008) 1.
  "An extra generation of ordinary fermions is excluded at the 6σ level on the basis of the S parameter alone."

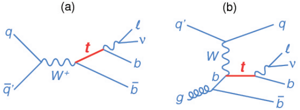
  (Taken a bit out of context!)
- Invisible decay width of Z boson
  $\rightsquigarrow$ 3 light neutrinos $\rightsquigarrow$ 3 generations of quarks and leptons
- Sharp drop in papers written on 4 generations

Single Top Production

- Renewed interest after observation of single top

DØ Collaboration, V. M. Abazov *et al.*, "Observation of Single Top-Quark Production," *Phys. Rev. Lett.* **103** (2009) 092001, arXiv:0903.0850.

$$\sigma(p\bar{p} \to tb + X, tqb + X) = 3.94 \pm 0.88 \text{ pb}$$



CDF Collaboration, T. Aaltonen *et al.*, "First Observation of Electroweak Single Top Quark Production," *Phys. Rev. Lett.* **103** (2009) 092002, arXiv:0903.0885.

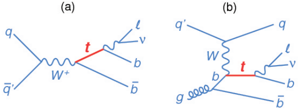
$$\sigma(p\bar{p} \to tb + X, tqb + X) = 2.3^{+0.6}_{-0.5} \text{ pb}$$

Single Top Production

- Renewed interest after observation of single top

DØ Collaboration, V. M. Abazov *et al.*, "Observation of Single Top-Quark Production," *Phys. Rev. Lett.* **103** (2009) 092001, arXiv:0903.0850.

$$\begin{aligned} |V_{tb}\, f_1^L| &= 1.07 \pm 0.12\,(\text{stat+syst}) \text{ assuming upper bound of } 1 \\ |V_{tb}| &> 0.78 \quad @95\% \text{ C.L. with no assumptions} \end{aligned}$$



CDF Collaboration, T. Aaltonen *et al.*, "First Observation of Electroweak Single Top Quark Production," *Phys. Rev. Lett.* **103** (2009) 092002, arXiv:0903.0885.

$$|V_{tb}| = 0.91 \pm 0.11\,(\text{stat+syst}) \pm 0.07\,(\text{theory})$$

Previous Measurements

- Previous measurements use unitarity relation and are not sensitive to new heavy quarks

DØ Collaboration, V. M. Abazov *et al.*, "Measurement of B($t \to$Wb) /B($t \to$ Wq) at $\sqrt{s} = 1.96$-TeV," *Phys. Lett.* **B639** (2006) 616–622,hep-ex/0603002.

$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 1.03^{+0.19}_{-0.17}$$

- Only sizable coupling of 4th generation is to 3rd generation:

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{matrix} \leftarrow & \sum V_{uq}^2 \simeq 1 \\ \leftarrow & \sum V_{cq}^2 \simeq 1 \\ \leftarrow & \sum V_{tq}^2 \gtrsim 0.78 \end{matrix}$$

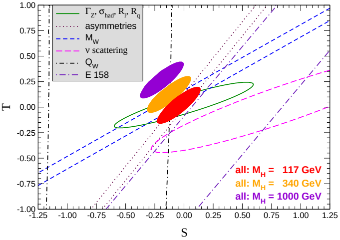
Is There a 4th Generation Allowed After All?

- Direct measurement of V_{tb} allows for sizable coupling between 3rd and 4th generation
- $N_G = 3$ from Invisible decay width of Z?
  Does not apply if neutrinos are heavier than $M_Z/2$
- The fourth neutrino so much heavier than the first three?
  Flavor sector of neutrinos not understood; take it as a hint!
- Bound from cosmology $\sum m_{\nu_i} \lesssim 2$ eV also assumes light neutrinos

Is There a 4th Generation Allowed After All?

- S and T parameter constraints can be evaded, but (!) only at the cost of some fine-tuning
- G. D. Kribs, T. Plehn, M. Spannowsky, and T. M. P. Tait, "Four generations and Higgs physics," *Phys. Rev.* **D76** (2007) 075016, arXiv:0706.3718.

  Constraints from S and T; latter constrains the mass difference; fourth generation allows for larger Higgs masses ☺



Particle Data Group Collaboration, C. Amsler *et al.*, *Phys. Lett.* **B667** (2008) 1.

$$\Delta S = \frac{N_c}{6\pi}\left(1 - Y \log \frac{m_u^2}{m_d^2}\right)$$

$$\Delta T = \frac{1}{8\pi \sin^2\theta_w \cos^2\theta_w}\left\{3\left[F_{t'b'} + \ldots\right]\right\}$$

Is There a 4th Generation Allowed After All?

- M. Bobrowski, A. Lenz, J. Riedl, and J. Rohrwild, "How much space is left for a new family of fermions?," *Phys. Rev.* **D79** (2009) 113006, arXiv:0902.4883.

  Constraints from FCNCs and $b \to s\gamma$; small mixing of 3rd and 4th family favored, but sizable mixing possible; suggests that electroweak precision observables should be considered

- M. S. Chanowitz, "Bounding CKM Mixing with a Fourth Family," *Phys. Rev.* **D79** (2009) 113008, arXiv:0904.3570.

  For $m_{t'} = 300$ GeV and $|m_{t'} - m_{b'}| \simeq 45 - 75$ GeV, mixing can be as large as $\sin\theta_{34} = 0.35$; global EWP fit; main constraints come from S, T; large(r) mixing as suggested by Bobrowski et al. excluded

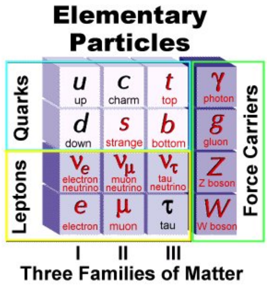
- J. Alwall *et al.*, "Is V(tb) = 1?," *Eur. Phys. J.* **C49** (2007) 791–801, hep-ph/0607115.

  $|V_{tb}| = 1$ need not necessarily hold; $|V_{tb}| > 0.9$; constraints from R_b, $B \to X_s\gamma$, S, T, U;

Time to Review What We Know from Theory!

Repetition of Families

Why is this pattern for 1 generation replicated 3 times? Horizontal symmetries?



Time to Review What We Know from Theory!

Mass Hierarchies and Yukawa Textures

up-quark mass $\sim 2 \times 10^{-3}$ GeV $\leftrightarrow$ top-quark mass ~ 172.3 GeV
Yukawa coupling of top ~ 1, but why are the other quarks so light?

Minimal mixing in quark sector

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 0.97 & 0.22 & 0.00 \\ 0.22 & 0.97 & 0.04 \\ 0.00 & 0.04 & ?? \end{pmatrix}$$

Time to Review What We Know from Theory!

Light neutrinos and texture of Yukawa couplings

Why are neutrinos so light?

$$\Delta m_\nu^2 \sim 10^{-2} - 10^{-5}\ \text{eV}, \quad \sum m_\nu < 2\ \text{eV}$$

Maximal mixing in lepton sector

$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \simeq \begin{pmatrix} 0.8 & 0.5 & 0.0 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix}$$

Why Consider a Fourth Family?

- Why not? No theoretical explanation for number of families
- Flavor sector not understood at all
- Obvious extension of the Standard Model
- Present experimental data does not exclude a 4th family
- May ease the tension between the lower bound of the Higgs mass and the EW precision fit

There are yet more reasons . . .

- V_{CKM} is now 4-by-4 $\rightsquigarrow$ More CPV $\rightsquigarrow$ EW baryogenesis?
- S. W. Ham, S. K. Oh, D. Son, "Electroweak Phase Transition in the MSSM with Four Generations," *Phys. Rev.* **D71** (2005) 015001, arXiv:hep-ph/0407019.

  $\exists$ parameter space, where EW phase transition strongly first order (otherwise baryon asymmetry washed out)

  Needs SUSY. Good, because we love SUSY! ☺
- W. S. Hou, "Source of CP Violation For Baryon Asymmetry of the Universe," arXiv:0803.1234.

  May work w/o SUSY
- R. Fok and G. D. Kribs, "Four Generations, the Electroweak Phase Transition, and Supersymmetry," *Phys. Rev.* **D78** (2008) 075023, arXiv:0803.4207 [hep-ph].

  Disagrees with Hou; SUSY indispensable; Ham/Oh/Son are in regime of non-perturbative b' Yukawa
- SUSY breaking difficult; see results later in talk . . . ☹

There are yet more reasons . . .

May help explain current B-physics data

W. S. Hou, M. Nagashima, G. Raz, A. Soddu, "Four Generation CP Violation in $B \to \phi K^0, \pi^0 K^0, \eta' K^0$ and Hadronic Uncertainties,", arXiv:hep-ph/0603097.

- Time dependent CP violation in B system
  Discrepancy between $b \to c\bar{c}s$ and $b \to sq\bar{q}$
- Direct CP violation in B system
  $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ should have similar rates, but they do not!
- Extra phases and t' contribution to EW penguin diagram may help
- Non-supersymmetric

There are yet more reasons ...

Non-perturbative physics

- If the 4th generation Yukawa couplings are dangerously close to the non-perturbative regime, maybe they are simply non-perturbative

  S. Bar-Shalom, G. Eilam, A. Soni, "Collider Signals of a Composite Higgs in the Standard Model with Four Generations,", arXiv:1001.0569.

- Higgs as composite particle of 4th generation quarks
- New collider signatures e.g. $H \to \bar{t}' t^* \to \bar{t}' b W^+$

Experimental Limits

We will be working with 3 sets of masses:

- From Tevatron and LEP @95% C.L.:

  Particle Data Group Collaboration, K. Nakamura *et al.*, JPG **37** 075021 (2010).

  $$m_{t'} \gtrsim 256 \text{ GeV}, \quad m_{b'} \gtrsim 128 \text{ GeV}, \quad m_{\tau'} \gtrsim 100.8 \text{ GeV}, \quad m_{\nu'_\tau} \gtrsim 45 \text{ GeV}$$

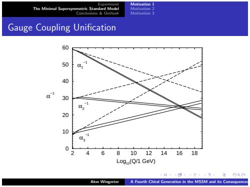
  Assumes t', b' decay into W and quark

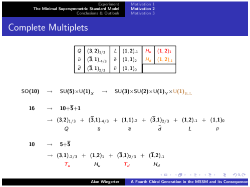
- Taken the most conservative bounds

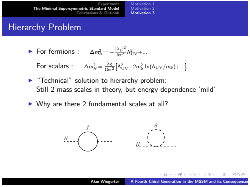
- T parameter $\rightsquigarrow |m_{t'} - m_{b'}| \simeq 45 - 75$ GeV

  $$m_{t'} = 256 \text{ GeV}, \quad m_{b'} = 181 \text{ GeV}, \quad m_{\tau'} = 100.8 \text{ GeV}$$

Soft SUSY Breaking Parameters







- Assume universal mass parameters at same scale!
  - m_0
  - $M_{1/2}$
  - a_0
  - $\tan\beta$ or equivalently b
  - $\text{sgn}\,\mu$
- Reduces number of parameters from 105 to 5! ☺

Toy mSUGRA/CMSSM Model with Four Generations

Godbole, Vempati, Wingerter arXiv:0911.1882

- Even with the most permissive bounds, we find that the MSSM w/four generations becomes non-perturbative $\sim$ 1000 TeV ☹
- To illustrate the *qualitative* features of mSUGRA4, we will calculate the spectrum
- Perturbativity studies require only RGE equations. For calculating the spectrum, we had to extend `SOFTSUSY` ($\rightarrow$ `Indisoft`).

Higgses [GeV]		Gauginos [GeV]		Squarks & Sleptons [GeV]					
h^0	119.5	$\widetilde{\chi}_1^0$	44.1	$\widetilde{u}_L$	480.4	$\widetilde{t}_1$	499.7	$\widetilde{t}'_1$	498.8
A^0	486.5	$\widetilde{\chi}_2^0$	83.4	$\widetilde{u}_R$	462.6	$\widetilde{t}_2$	357.8	$\widetilde{t}'_2$	356.4
H^0	486.2	$\widetilde{\chi}_3^0$	474.2	$\widetilde{d}_L$	486.7	$\widetilde{b}_1$	432.4	$\widetilde{b}'_1$	428.7
$H^\pm$	492.8	$\widetilde{\chi}_4^0$	478.1	$\widetilde{d}_R$	462.0	$\widetilde{b}_2$	465.9	$\widetilde{b}'_2$	466.2
		$\widetilde{\chi}_1^\pm$	83.4	$\widetilde{e}_L$	187.7	$\widetilde{\tau}_1$	196.4	$\widetilde{\tau}'_1$	196.2
		$\widetilde{\chi}_2^\pm$	481.4	$\widetilde{e}_R$	142.0	$\widetilde{\tau}_2$	126.5	$\widetilde{\tau}'_2$	127.1
		$\widetilde{g}$	352.1	$\widetilde{\nu}_e$	170.4	$\widetilde{\nu}_\tau$	169.6	$\widetilde{\nu}'_\tau$	169.6

Toy mSUGRA/CMSSM Model with Four Generations

Godbole, Vempati, Wingerter arXiv:0911.1882

Higgses [GeV]		Gauginos [GeV]		Squarks & Sleptons [GeV]			
h^0	106.7	$\widetilde{\chi}_1^0$	96.6	$\widetilde{u}_L$	568.2	$\widetilde{t}_1$	587.4
A^0	382.2	$\widetilde{\chi}_2^0$	178.3	$\widetilde{u}_R$	547.5	$\widetilde{t}_2$	411.0
H^0	382.6	$\widetilde{\chi}_3^0$	343.0	$\widetilde{d}_L$	573.6	$\widetilde{b}_1$	519.9
$H^\pm$	390.9	$\widetilde{\chi}_4^0$	362.8	$\widetilde{d}_R$	546.6	$\widetilde{b}_2$	547.2
		$\widetilde{\chi}_1^\pm$	178.0	$\widetilde{e}_L$	205.7	$\widetilde{\tau}_1$	209.1
		$\widetilde{\chi}_2^\pm$	364.5	$\widetilde{e}_R$	146.7	$\widetilde{\tau}_2$	138.9
		$\widetilde{g}$	607.0	$\widetilde{\nu}_e$	189.8	$\widetilde{\nu}_\tau$	189.1

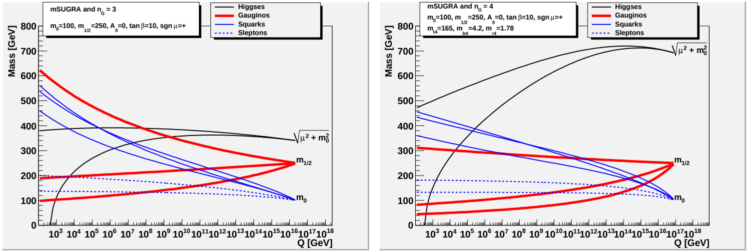
Table: mSUGRA3 with $m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, sgn μ=+. $M_{\mathrm{GUT}} = 2.40 \times 10^{16}$ GeV.

Higgses [GeV]		Gauginos [GeV]		Squarks & Sleptons [GeV]					
h^0	119.5	$\widetilde{\chi}_1^0$	44.1	$\widetilde{u}_L$	480.4	$\widetilde{t}_1$	499.7	$\widetilde{t}'_1$	498.8
A^0	486.5	$\widetilde{\chi}_2^0$	83.4	$\widetilde{u}_R$	462.6	$\widetilde{t}_2$	357.8	$\widetilde{t}'_2$	356.4
H^0	486.2	$\widetilde{\chi}_3^0$	474.2	$\widetilde{d}_L$	486.7	$\widetilde{b}_1$	432.4	$\widetilde{b}'_1$	428.7
$H^\pm$	492.8	$\widetilde{\chi}_4^0$	478.1	$\widetilde{d}_R$	462.0	$\widetilde{b}_2$	465.9	$\widetilde{b}'_2$	466.2
		$\widetilde{\chi}_1^\pm$	83.4	$\widetilde{e}_L$	187.7	$\widetilde{\tau}_1$	196.4	$\widetilde{\tau}'_1$	196.2
		$\widetilde{\chi}_2^\pm$	481.4	$\widetilde{e}_R$	142.0	$\widetilde{\tau}_2$	126.5	$\widetilde{\tau}'_2$	127.1
		$\widetilde{g}$	352.1	$\widetilde{\nu}_e$	170.4	$\widetilde{\nu}_\tau$	169.6	$\widetilde{\nu}'_\tau$	169.6

Table: mSUGRA4 with $m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, sgn μ=+, and all 4th generation masses equal to their 3rd generation counterparts (toy model). $M_{\mathrm{GUT}} = 8.82 \times 10^{16}$ GeV.

Toy mSUGRA/CMSSM Model with Four Generations

Godbole, Vempati, Wingerter arXiv:0911.1882



(a) Three generations.

(b) Four generations.

Figure: The running of the various soft masses in the MSSM3 and MSSM4 is shown in the left and right panel, respectively. The unification scale is $M_{\rm GUT} = 2.40 \times 10^{16}$ GeV and $M_{\rm GUT} = 8.82 \times 10^{16}$ GeV in the case of three and four generations, respectively.

Perturbativity of the Yukawa Couplings

Godbole, Vempati, Wingerter arXiv:0911.1882

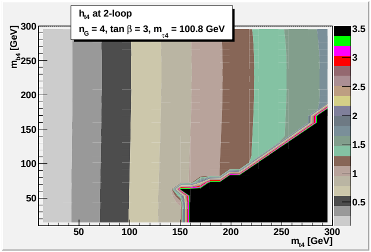


Figure: Constraints in the $m_{b'}$–$m_{t'}$ plane from the perturbativity of $h_{t'}$ for fixed values of $m_{\tau'} = 100.8$ GeV and $\tan\beta = 3$.

Perturbativity of the Yukawa Couplings

Godbole, Vempati, Wingerter arXiv:0911.1882

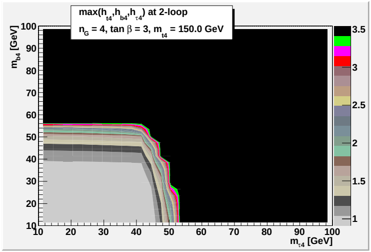


Figure: Constraints in the $m_{\tau'}$–$m_{b'}$ plane from the perturbativity of $h_{t'}$, $h_{b'}$, and $h_{\tau'}$ for fixed values of $m_{t'} = 150$ GeV and $\tan\beta = 3$.

Perturbativity of the Yukawa Couplings

Godbole, Vempati, Wingerter arXiv:0911.1882

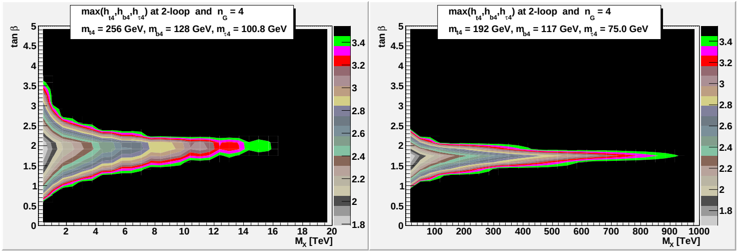


Figure: For the masses that are (i) experimentally allowed, (ii) that are $\sim 25\%$ below the experimental lower bounds *with* T-parameter constraints.

Minimal Gauge Mediated Supersymmetry Breaking

- Theory becomes non-perturbative $\sim 10 - 1000$ TeV
- 4th chiral generation and perturbative unification mutually exclusive
- mSUGRA/CMSSM does not work
- Need SUSY breaking mechanism with low scale
- Gauge Mediated Supersymmetry Breaking
- Consider minimal model

Minimal Gauge Mediated Supersymmetry Breaking

Spectrum generated with `Indisoft` — Godbole, Vempati, Wingerter arXiv:0911.1882

Higgses [GeV]		Gauginos [GeV]		Squarks & Sleptons [GeV]					
h^0	46.2	$\widetilde{\chi}_1^0$	64.3	$\widetilde{u}_L$	758.1	$\widetilde{t}_1$	766.1	$\widetilde{t}'_1$	722.6
A^0	507.6	$\widetilde{\chi}_2^0$	127.0	$\widetilde{u}_R$	735.5	$\widetilde{t}_2$	639.3	$\widetilde{t}'_2$	583.8
H^0	532.2	$\widetilde{\chi}_3^0$	640.6	$\widetilde{d}_L$	761.1	$\widetilde{b}_1$	725.1	$\widetilde{b}'_1$	733.4
$H^\pm$	516.1	$\widetilde{\chi}_4^0$	655.1	$\widetilde{d}_R$	733.8	$\widetilde{b}_2$	734.3	$\widetilde{b}'_2$	525.5
		$\widetilde{\chi}_1^\pm$	126.9	$\widetilde{e}_L$	208.3	$\widetilde{\tau}_1$	208.4	$\widetilde{\tau}'_1$	320.3
		$\widetilde{\chi}_2^\pm$	652.0	$\widetilde{e}_R$	88.1	$\widetilde{\tau}_2$	87.8	$\widetilde{\tau}'_2$	193.4
		$\widetilde{g}$	438.4	$\widetilde{\nu}_e$	197.2	$\widetilde{\nu}_\tau$	197.2	$\widetilde{\nu}'_\tau$	202.7

Table: Minimal GMSB spectrum with 4 generations: $n_5 = 1$, $M_{\text{mess}} = 100$ TeV, $\Lambda = 50$ TeV, $\tan\beta = 1.75$, sgn $\mu = +$. $\widetilde{\tau}'$ is tachyonic, $m_h = 46.2$ GeV, $m_{\widetilde{G}} = 1.2 \times 10^{-9}$ GeV (gravitino), NLSP is neutralino.

Minimal Gauge Mediated Supersymmetry Breaking

Godbole, Vempati, Wingerter arXiv:0911.1882

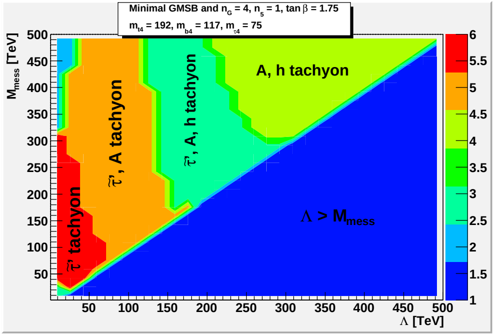


Figure: Regions in mGMSB parameter space Λ–M_{mess}. The lower-diagonal part is ruled out as $\Lambda > M_{\text{mess}}$. In the upper-diagonal part, from left to right, the first region (red) tachyonic τ', and the second (orange), third (cyan), fourth (green) do not have consistent radiative electroweak symmetry breaking as indicated by the tachyonic Higgses.

Conclusions

- 4th generation not favored by experiment, but not excluded
- Obvious extension of the Standard Model
- May addresses some questions like
  - Higgs bound $\leftrightarrow$ electroweak precision data
  - Electroweak baryogenesis
  - B-physics data
- Needs fine-tuned masses to avoid S and T parameter constraints
- Difficult to accommodate in the context of SUSY (breaking)