A Fourth Chiral Generation in the MSSM and its Consequences for SUSY Breaking

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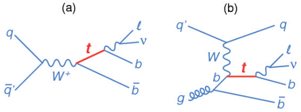
Talk based on *JHEP* 03 (2010) 023 (arXiv:0911.1882)

Single Top Production

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

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



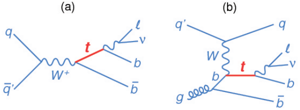
CDF Collaboration, T. Aaltonen *et al.*, "First Observation of Electroweak Single Top Quark Production," *Phys. Rev. Lett.* **103** (2009) 092002, arXiv:0903.0885.

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

Single Top Production

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

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



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

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

Direct Measurement of $|V_{tb}|$ Constrains 4G Models

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

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

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

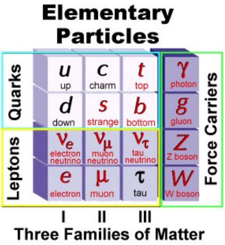
- Only sizable coupling of 4th generation is to 3rd generation:

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

What Do We Know from Theory?

Repetition of Families

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



What Do 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

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 0.97 & 0.22 & 0.00 \\ 0.22 & 0.97 & 0.04 \\ 0.00 & 0.04 & 0.99 \end{pmatrix}$$

What Do 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

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

Why Consider a Fourth Family?

- Why not? No theoretical explanation for number of families
- Obvious extension of the Standard Model
- Present experimental data does not exclude a 4th family with sizable couplings to the 3rd family
- May ease the tension between the lower bound of the Higgs mass and the EW precision fit ($\rightarrow$ see next transparencies)
- May help explain current B-physics data
- Electroweak baryogenesis may be viable (under debate)
  R. Fok and G. D. Kribs, "Four Generations, the Electroweak Phase Transition, and Supersymmetry," *Phys. Rev.* **D78** (2008) 075023, arXiv:0803.4207 [hep-ph].
- Dynamical electroweak symmetry breaking
- ...

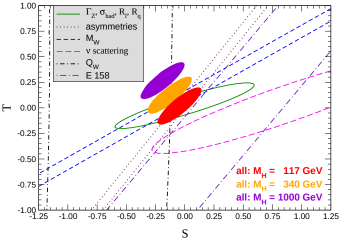
Previous Work on 4th Generation

- 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;

- 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.

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

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

Previous Work on 4th Generation

- 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 $b \rightarrow s\gamma$; 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

Experimental Limits

We will be working with 3 sets of masses:

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

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

  Assumes t', b' decay into W and quark

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

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

- Pole mass vs. running mass and lower confidence levels

  $$m_{t'} = 192 \text{ GeV}, \quad m_{b'} = 117 \text{ GeV}, \quad m_{\tau'} = 75 \text{ GeV}$$

What is a Fourth Family?

People mean different things and some care is required

- Vector-like right-handed 4th top, i.e. $\bar{t}'_R$ and t'_R

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

- Vector-like 4th family ("mirror family"): Very popular in string theory

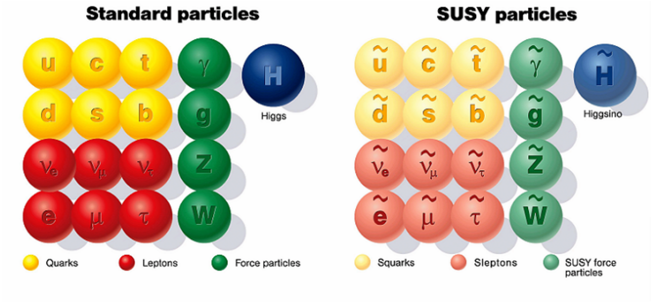
  T. Ibrahim and P. Nath, "An MSSM Extension with a Mirror Fourth Generation, Neutrino Magnetic Moments and LHC Signatures," *Phys. Rev.* **D78** (2008) 075013, arXiv:0806.3880.

- Leptons w/o baryons and vice versa

  C. D. Froggatt, D. J. Smith, and H. B. Nielsen, "Could there be a fourth generation of quarks without more leptons?,"
  Z. Phys. **C73** (1997) 333–337, arXiv:hep-ph/9603436.

- Finally: Chiral 4th family, i.e. replica of 3rd family, but different masses
  $\longrightarrow$ This is what my talk is about!
  $\longrightarrow$ One more thing: SUSY

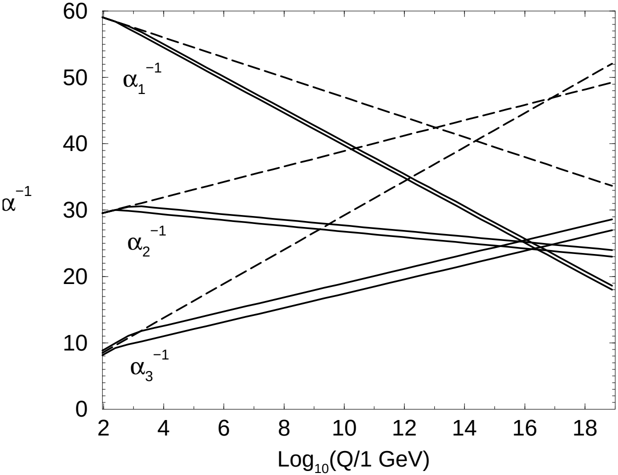
The Minimal Supersymmetric Standard Model



- Addresses quite a few of the problems of the Standard Model
- Comes at a high price: 105 additional parameters!
- Let us review the motivation behind it

Gauge Coupling Unification

S. P. Martin, "A Supersymmetry Primer," arXiv:hep-ph/9709356.



Complete Multiplets

Q	$(\mathbf{3},\mathbf{2})_{1/3}$	L	$(\mathbf{1},\mathbf{2})_{-1}$	H_u	$(\mathbf{1},\mathbf{2})_{1}$
$\bar{u}$	$(\bar{\mathbf{3}},\mathbf{1})_{-4/3}$	$\bar{e}$	$(\mathbf{1},\mathbf{1})_{2}$	H_d	$(\mathbf{1},\mathbf{2})_{-1}$
$\bar{d}$	$(\bar{\mathbf{3}},\mathbf{1})_{2/3}$	$\bar{\nu}$	$(\mathbf{1},\mathbf{1})_{0}$		

$$\mathrm{SO}(\mathbf{10}) \quad\rightarrow\quad \mathrm{SU}(\mathbf{5})\times\mathrm{U}(\mathbf{1})_X \quad\rightarrow\quad \mathrm{SU}(\mathbf{3})\times\mathrm{SU}(\mathbf{2})\times\mathrm{U}(\mathbf{1})_Y\times\mathrm{U}(\mathbf{1})_{\mathrm{B\text{-}L}}$$

$$\mathbf{16} \quad\rightarrow\quad \mathbf{10}+\bar{\mathbf{5}}+\mathbf{1}$$

$$\rightarrow \underbrace{(\mathbf{3},\mathbf{2})_{1/3}}_{Q} + \underbrace{(\bar{\mathbf{3}},\mathbf{1})_{-4/3}}_{\bar{u}} + \underbrace{(\mathbf{1},\mathbf{1})_{-2}}_{\bar{e}} + \underbrace{(\bar{\mathbf{3}},\mathbf{1})_{2/3}}_{\bar{d}} + \underbrace{(\mathbf{1},\mathbf{2})_{-1}}_{L} + \underbrace{(\mathbf{1},\mathbf{1})_{0}}_{\bar{\nu}}$$

$$\mathbf{10} \quad\rightarrow\quad \mathbf{5}+\bar{\mathbf{5}}$$

$$\rightarrow \underbrace{(\mathbf{3},\mathbf{1})_{-2/3}}_{T_u} + \underbrace{(\mathbf{1},\mathbf{2})_{1}}_{H_u} + \underbrace{(\bar{\mathbf{3}},\mathbf{1})_{2/3}}_{T_d} + \underbrace{(\bar{\mathbf{1}},\mathbf{2})_{-1}}_{H_d}$$

Hierarchy Problem

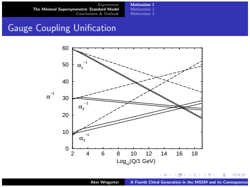
- For fermions : $\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots$

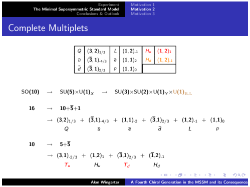
  For scalars : $\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2 - 2m_S^2 \ln(\Lambda_{\mathrm{UV}}/m_S) + \ldots\right]$

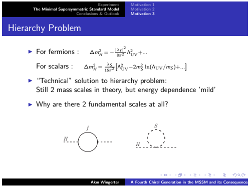
- "Technical" solution to hierarchy problem:
  Still 2 mass scales in theory, but energy dependence 'mild'

- Why are there 2 fundamental scales at all?

Reducing the Number of Parameters

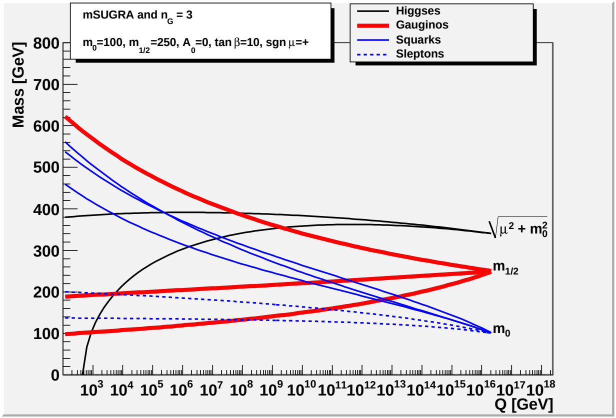






- SO$(\mathbf{10})$ or not, the gauge couplings seem to unify!
- Assume universal mass parameters at same scale!
  - m_0
  - $M_{1/2}$
  - a_0
  - $\tan\beta$ or equivalently b
  - sgn μ
- Reduces number of parameters from 105 to 5!

mSUGRA "Inspired" Boundary Conditions



Perturbativity of the Yukawa Couplings

Godbole, Vempati, Wingerter arXiv:0911.1882

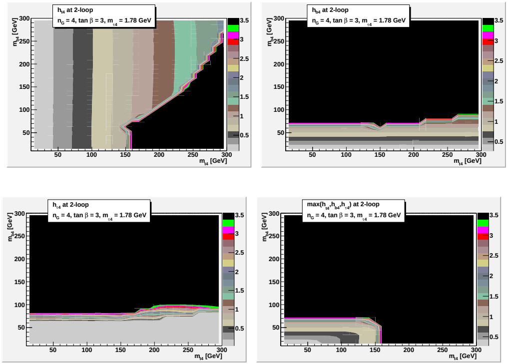


Figure: $h_{t'}$, $h_{b'}$, $h_{\tau'}$ in MSSM4 at 2-loop and $M_X = 2.3 \times 10^{16}$ GeV, $\tan\beta = 3$ and $m_{\tau'} = m_\tau = 1.78$ GeV. ϟ

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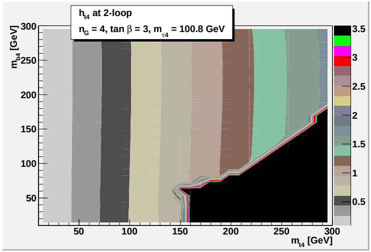

Figure: Constraints in the $m_{b'}$–$m_{t'}$ plane from the perturbativity of $h_{t'}$ for fixed values of $m_{\tau'} = 100.8$ GeV and $\tan\beta = 3$.

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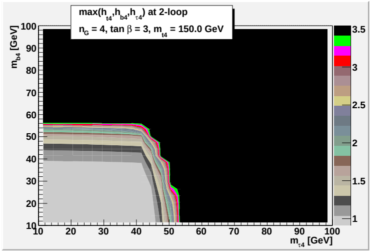

Figure: Constraints in the $m_{b'}$–$m_{t'}$ plane from the perturbativity of $h_{t'}$, $h_{b'}$, and $h_{\tau'}$ for fixed values of $m_{\tau'} = 100.8$ GeV and $\tan\beta = 3$.

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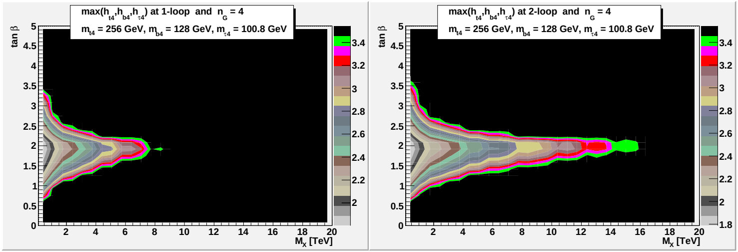

Figure: For the current experimental lower bounds on the 4th generation fermion masses *without* T-parameter constraints.

Perturbativity of the Yukawa Couplings

Godbole, Vempati, Wingerter arXiv:0911.1882

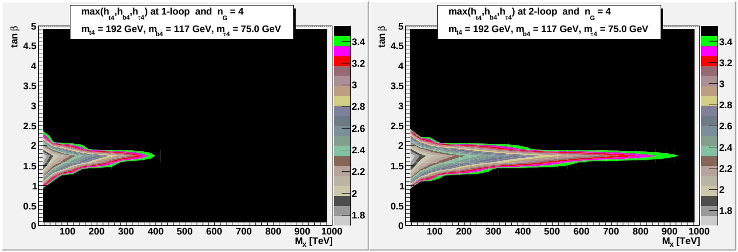

Figure: For the masses that are $\sim 25\%$ below the experimental lower bounds *with* T-parameter constraints.

Perturbativity of the Yukawa Couplings

Many "typoish" claims in the literature:

- Unification w/o SUSY

  P. Q. Hung, "Minimal SU(5) resuscitated by long-lived quarks and leptons," *Phys. Rev. Lett.* **80** (1998) 3000–3003, arXiv:hep-ph/9712338.

  Reiterated in the recent literature

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

  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.

  Does not work with present experimental lower bounds!

- General expectation is that w/SUSY everything is better

  Seems to be true only for Higgs sector!

- Range of perturbativity

  Z. Murdock, S. Nandi, and Z. Tavartkiladze, "Perturbativity and a Fourth Generation in the MSSM," *Phys. Lett.* **B668** (2008) 303–307, arXiv:0806.2064.

  Our result indicates that the range of perturbativity lies 4 orders of magnitude below the value given by Murdock et al.

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

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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
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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.

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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

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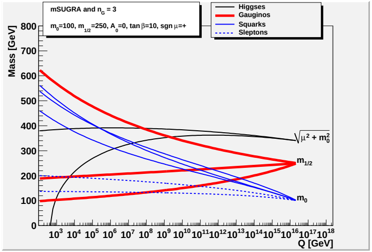
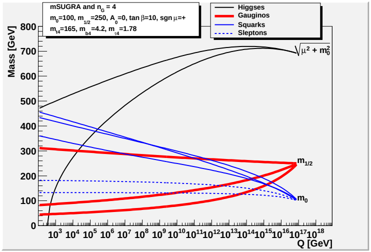
Table: mSUGRA4 with $m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, sgn $\mu{=}{+}$, and all 4th generation masses equal to their 3rd generation counterparts (toy model). $M_{\rm GUT} = 8.82 \times 10^{16}$ GeV.

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 $M_{\text{GUT}} = 2.40 \times 10^{16}$ GeV and $M_{\text{GUT}} = 8.82 \times 10^{16}$ GeV in the case of three and four generations, respectively.

Minimal Gauge Mediated Supersymmetry Breaking

- Theory becomes non-perturbative ~ 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

Godbole, Vempati, Wingerter arXiv:0911.1882

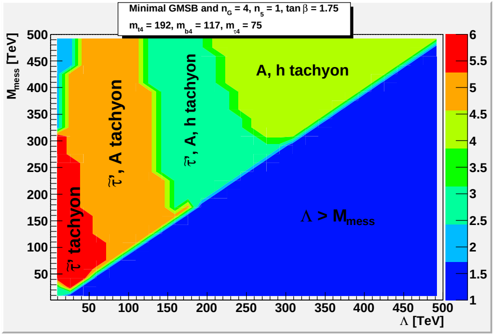


Figure: Regions in mGMSB parameter space Λ–M_{mess}. The lower-diagonal part is ruled out as $\Lambda > M_{\text{mess}}$. In the upper-diagonal part, from left to right, the first region (red) tachyonic τ', and the second (orange), third (cyan), fourth (green) do not have consistent radiative electroweak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

Minimal Gauge Mediated Supersymmetry Breaking

Godbole, Vempati, Wingerter arXiv:0911.1882

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

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

Conclusions

- 4th generation not favored by experiment, but not excluded
- Obvious extension of the Standard Model
- Addresses many open problems like
  - Higgs bound $\leftrightarrow$ electroweak precision data
  - Electroweak baryogenesis (?)
  - B-physics data
- Seems difficult to accommodate in the context of SUSY
- 4th chiral generation and perturbative unification (mSUGRA/CMSSM) mutually exclusive
- Gauge mediation w/generalized boundary conditions may work