Non-Degenerate Squarks & A Heavy Higgs in Flavored GMSB

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arXiv:1209.4904 [hep-ph] with: M. Abdullah, Y. Shadmi and Y. Shirman
arXiv:1306.6631 [hep-ph] with: G. Perez and Y. Shadmi

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Gauge Mediated SUSY Breaking (GMSB)

The GMSB superpotential Dine, Nelson & Shirman arXiv:hep-ph/9408384

Dine, Nelson, Nir & Shirman arXiv:hep-ph/9507378.

$$W = X\phi\bar{\phi} + Y^u QH_u u^c + Y^d QH_d d^c + Y^l LH_d e^c$$

where $X = M + \theta^2 F$ parametrizes ~~SUSY~~
and $\phi, \bar{\phi}$ - vector like pair of SU(5)

Main Features

$$(\tilde{m}^2_{soft})_{i,j} = \delta_{i,j}\tilde{m}^2, \qquad A^{u,d,l}_{i,j} = 0 \qquad \text{at} \quad \mu = M$$

Evolving down with RGEs

Minimally Flavor Violating(MFV) Theory

In this talk

Extend: GMSB

$\Downarrow$

Flavored GMSB (FGM)

Schematics

Yukawa-like messenger-matter couplings

$$\phi_i = \begin{pmatrix} T \\ \bar{D} \end{pmatrix} \qquad \bar{\phi}_i = \begin{pmatrix} \bar{T} \\ D \end{pmatrix} \quad \Longrightarrow \quad \Delta W_{FGM} \supset \quad y^u Q \bar{D} u^c, \quad y^d Q D d^c$$

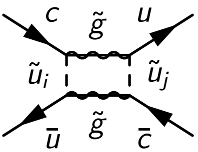
Upshot

flavor dependent

1. new scalar soft-mass contributions $\rightarrow$ non-degenerate squarks
2. non-zero A-terms $\rightarrow$ a heavy higgs (& light squarks)

Flavor Issues

<u>Low-E observables constrain the SUSY flavor structure</u>



$$\Longrightarrow \quad \delta_{ij} = \frac{(\Delta\tilde{m}^2)_{ij}\ K_{ij}}{\bar{m}^2} \quad \Longleftrightarrow$$

- Degeneracy
- Alignment
- Decoupling

In this work: Y's and y's from symmetry

- Explain SM mass hierarchies & mixings $\rightarrow$ flavor symmetry
- same flavor symmetry $\rightarrow$ control new couplings

(Back of our mind - Froggatt-Nielsen mechanism)

1st stop: a heavy Higgs

Abdullah, IG, Shadmi & Shirman, arXiv:1209.4904 [hep-ph]

- Evans, Ibe & Yanagida
- Kang, Li, Liu, Tong & Yang
- Craig, Knapen, Shih & Zhao
- Albaid & Babu
- Craig, Knapen & Shih
- Evans & Shih
- ...

Motivation - The Higgs Mass

In the MSSM at 1-loop

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

where

$$M_S^2 = m_{\tilde{t}_1} m_{\tilde{t}_2} \qquad \& \qquad X_t = A_t - \mu \cot\beta$$

Implication for $m_h = 125$ GeV

large M_S or large $\frac{X_t}{M_S}$

In GMSB - no A-terms $\Longrightarrow$ Heavy $\tilde{t}$(all squarks) $\sim 8 - 10$ TeV

for 3-loops see Feng et. al. arXiv:1306.2318 [hep-ph]

MFV-like FGM

so for $m_h \approx 125$ GeV

need access to stop sector: $A_t, \tilde{m}^2_{q_3}, \tilde{m}^2_t$

Simplest example: MFV-like

$\bar{D}$, H_u: same flavor transformation

$$y^u \sim Y^u \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Main Features

$$W = X(\bar{T}_i T_i + \bar{D}_i + D_i) \quad + \quad Y^u Q H_u u^c + Y^d Q H_d d^c + Y^l L H_d e^c$$
$$+ \quad y^u Q \bar{D} u^c$$

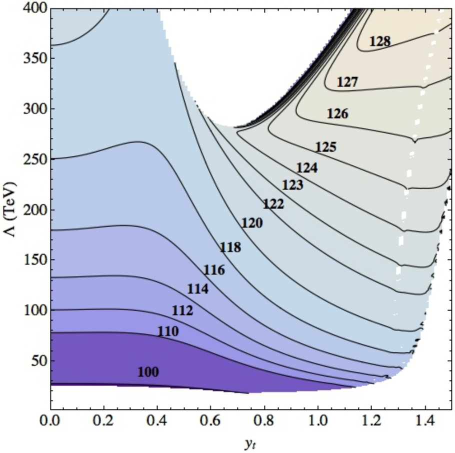
At $\mu = M$:

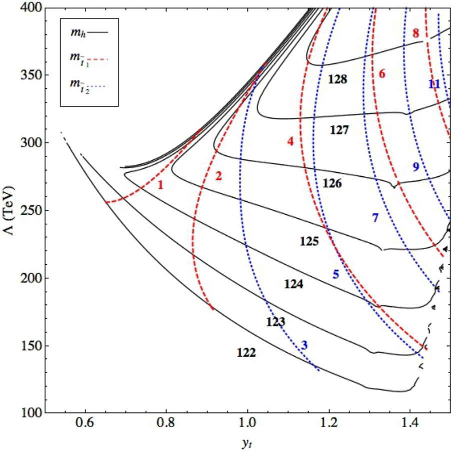
- non-zero A-terms
$$A \sim -\frac{1}{(4\pi)^2} Y y^2 \frac{F}{M}$$
- soft masses$\Big|_{2-loop}$:
$$\tilde{m}^2 \sim \frac{1}{(4\pi)^4} \left(g^4 - g^2 y^2 + y^4 \pm Y^2 y^2\right) \left|\frac{F}{M}\right|^2$$
- soft masses$\Big|_{1-loop}$: (for $M < 10^7$ GeV)
$$\tilde{m}^2 \sim -\frac{y^2}{(4\pi)^2} \frac{F^4}{M^6}$$

MFV-like: Heavy Higgs & $\sim$ TeV Spectra

Abdullah, IG, Shadmi & Shirman, arXiv:1209.4904 [hep-ph]

$\underline{A_{33}, \tilde{m}^2_{33}} \quad \Longrightarrow \quad \underline{M = 900 \text{ TeV}, \tan\beta = 10}$





Spectrum

Examples with:

1. squarks and gluinos with masses ≤ 2.5 TeV
2. some sleptons & EW gauginos ≤ 500 GeV

accessible at 14 TeV LHC

2nd stop: non-degenerate squarks

IG, G. Perez and Y. Shadmi arXiv:1306.6631 [hep-ph]

Motivation - MFV Vs. Non-MFV

In theories which are MFV:

$$\tilde{m}^2 \sim \mathbb{I} + \# YY^\dagger$$

- degenerate 1st & 2nd generations
- no mixing

Most SUSY searches - tuned for an MFV spectrum

For 8-fold degenerate squarks

Rough bounds (various simplified models):

$$m_{\tilde{g}} \gtrsim 1.2 \text{ TeV}, \qquad m_{\tilde{q}} \gtrsim 800 \text{ GeV}, \qquad m_{\tilde{t}} \gtrsim 500 \text{ GeV}$$

Motivation - SUSY Searches

MFV is over constraining:

bounds on $\delta_{ij} = \frac{(\Delta\tilde{m}^2)_{ij} \ K_{ij}}{\bar{m}^2}$ allow: small mixing $\Leftrightarrow$ large splitting

non-MFV Squarks at LHC searches

Production: X-sections affected by non-degenerate 1^{st} 2^{nd} gen squarks. Bounds: usually assume 8-fold degeneracy, but in fact mainly sensitive to up & down (PDFs)

Detection:

- lighter squarks: efficiency reduced
  Mahbubani, Papucci, Perez, Ruderman & Weiler arXiv:1212.3328 [hep-ph]
- mixings affect detection (especially for $\tilde{t}, \tilde{b}, \tilde{c}$)
  Blanke, Giudice, Paradisi, Perez & Zupan arXiv:1302.7232 [hep-ph]], Agrawal & Frugiuele arXiv:1304.3068 [hep-ph]]
- Slepton searches: Flavor-subtraction doesn't work, kinematic edges: split and mixed Galon & Shadmi arXiv:1108.2220 [hep-ph]

Flavor Symmetry

Flavor symmetry $U(1) \otimes U(1)$ with spurions $S_1(-1,0)$, $S_2(0,-1)$

Charges, following Leurer-Nir-Seiberg

$$\begin{array}{lll} Q_1(6,-3) & , Q_2(2,0) & , Q_3(0,0) \\ u_1^c(-6,9) & , u_2^c(-2,3) & , u_3^c(0,0) \\ d_1^c(-6,9) & , d_2^c(2,0) & , d_3^c(2,0) \end{array} \qquad H_u(0,0) \quad , H_d(0,0)$$

produce quark masses and V_{CKM}

$$Y_U \sim \begin{pmatrix} \lambda^6 & \lambda^4 & 0 \\ 0 & \lambda^3 & \lambda^2 \\ 0 & 0 & 1 \end{pmatrix} \, , \quad Y_D \sim \begin{pmatrix} \lambda^6 & 0 & 0 \\ 0 & \lambda^4 & \lambda^4 \\ 0 & \lambda^2 & \lambda^2 \end{pmatrix}$$

(up to $\mathcal{O}(1)$ coefficients)

Flavor Symmetry

Assign messenger charges

$$D(m,-n), \quad \bar{D}(-m,n)$$

to determine the pattern of

$$y^u \Longrightarrow \Delta\tilde{m}_u^2 \supset y^{u\dagger}y^u y^{u\dagger}y^u, \quad y^{u\dagger}YY^\dagger y^u, \quad Y^\dagger y^u y^{u\dagger}Y, \quad g^2 y^{u\dagger}y^u, \ldots$$

such that

- Y's and $\Delta\tilde{m}^2_{q,u,d}$ are approximately diagonal in the same basis
- $\Delta\tilde{m}^2$ exhibits large splitting & small mixing

Note: SUSY alignment - low scale models

Specific Models

Light charm- and strange-squarks

$$\underline{D(-1,3),\ \bar{D}(1,-3)} \implies y_u \sim \begin{pmatrix} \lambda^4 & 0 & 0 \\ 0 & c_{22}\lambda & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Heavy up- and down-squarks

$$\underline{D(0,6),\ \bar{D}(0,-6)} \implies y_u \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

A light right-handed charm squark and a heavy Higgs

$$\underline{D(-2,3),\ \bar{D}(2,3)} \implies y_u \sim \begin{pmatrix} \lambda^5 & 0 & 0 \\ 0 & \lambda^2 & 0 \\ 0 & y & 0 \end{pmatrix}$$

Non-Degenerate Squarks

IG, Perez & Shadmi, arXiv:1306.6631 [hep-ph]

Choose (m, n) such that

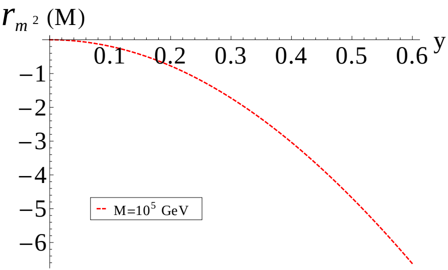
$$(y_u)_{ij} \approx y\delta_{i2}\delta_{j2}$$

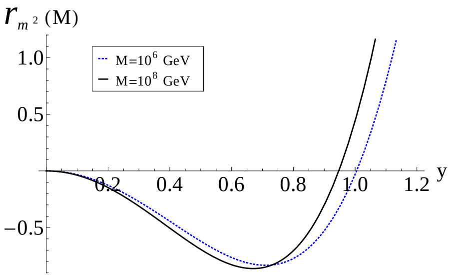
$\Longrightarrow$

Then

$$(\Delta m_q^2)_{22} = \tfrac{1}{2}(\Delta m_u^2)_{22} \equiv \delta m^2$$

For $r_{m^2} = \frac{\delta m^2}{m^2_{\mathrm{GMSB}}}$ $(N_5 = 1)$





Non-Degenerate Squarks - Running Effects

For low scale models

- r_{m^2} can be large for relatively small y's
- less running $\rightarrow$ less (RG) degeneracy

Examples: ($N_5 = 1$ (light gluino), $\tan\beta = 5$)

1. $M = 500$ TeV, $F/M = 200$ TeV

$$m_q \sim 2 \text{ TeV}, \quad m_{\tilde{g}} \sim 1.5 TeV, \quad \tilde{c}_R \sim 870 \text{ GeV}$$

2. $M = 400$ TeV, $F/M = 150$ TeV

$$m_q \sim 1.6 \text{ TeV}, \quad m_{\tilde{g}} \sim 1.2 TeV, \quad \tilde{c}_R \sim 670 \text{ GeV}$$

Conclusions

- Flavored Gauge Mediation (FGM) allows viable non-MFV models with some degree of mass splitting and mixings
- with low scale supersymmetric alignment you can get large mass splitting (unlike high-scale)
- non-zero A-terms at $\mu = M$ can contribute to 125 GeV Higgs mass with superpartners accessible at the LHC
- FGM models lead to interesting squark and slepton masses

Thank You

Formula for mass splitting

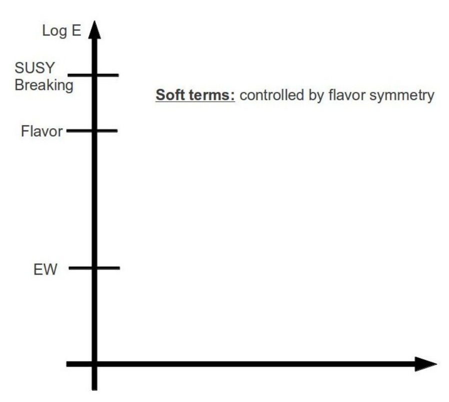
$$\delta m^2 \sim -\frac{1}{(4\pi)^2}\frac{1}{6}|y|^2\frac{F^4}{M^6} + \frac{1}{(4\pi)^4}\left(6|y|^2 - G_y\right)|y|^2\frac{F^2}{M^2}\,,$$

where

$$G_y \equiv \frac{16}{3}g_3^2 + 3g_2^2 + \frac{13}{15}g_1^2\,.$$

Alignment

Usual Alignment

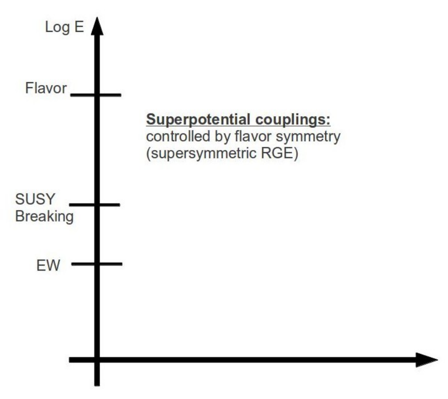


Nir & Seiberg arXiv:hep-ph/9304307

- high scale ~~*SUSY*~~
- aligned soft terms
- **mild splittings**

Supersymmetric Alignment

Usual Alignment

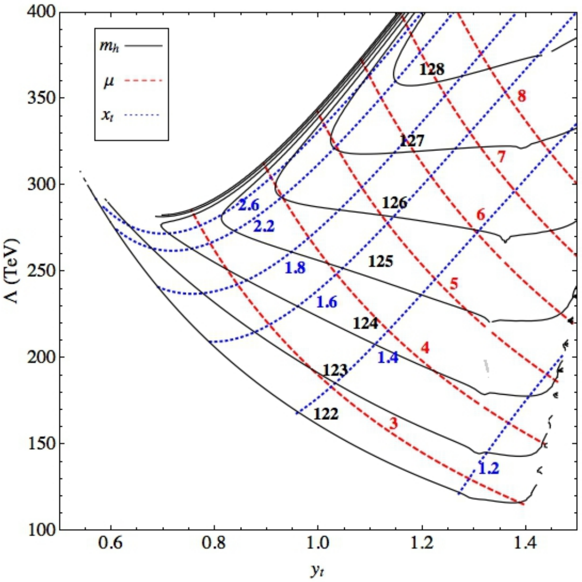


Shadmi & Szabo arXiv: 1103.0292 [hep-ph]

- low-scale ~~*SUSY*~~
- aligned superpotential couplings
- soft-terms "inherit" structure
- **large splittings**

Other Higgs Plots $\Longrightarrow$

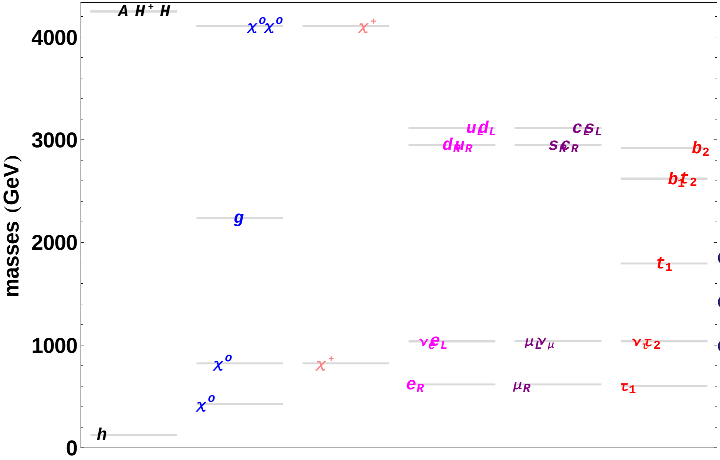
Higgs Mass - Plots



$M = 900$ TeV, $\tan\beta = 10$

- $x_t = \frac{X_t}{M_S}$ large close to edge

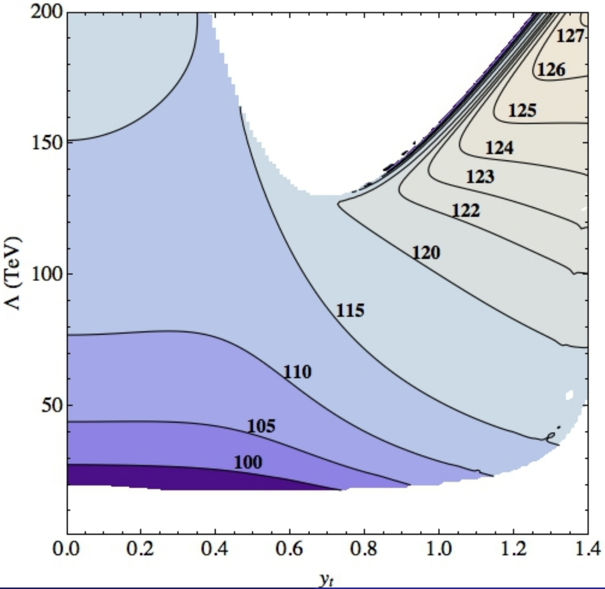
Example Spectrum



$$\underline{M = 900 \text{ TeV}}$$
$$\underline{\Lambda = 3.03 \text{ TeV}}$$
$$\underline{\tan\beta = 10}$$
$$\underline{y_t = 0.92}$$

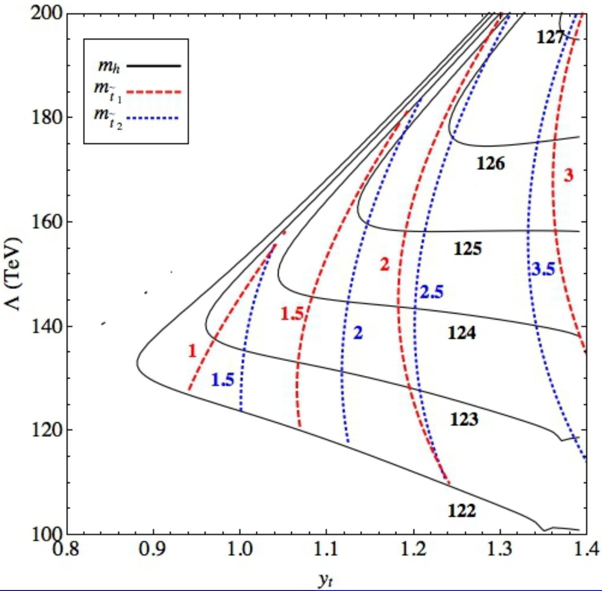
- $m_{\chi^0} = 425$ GeV
- $m_{\tilde{t}_1} = 1795$ GeV
- $m_{\tilde{g}} = 2240$ GeV

Plots



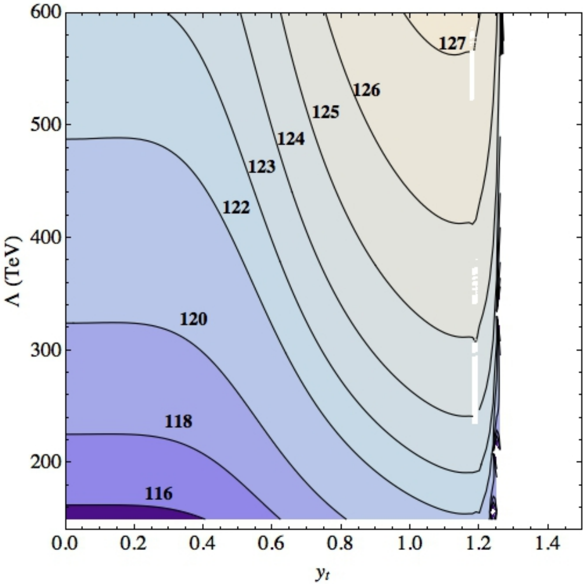
$M = 400$ TeV, $\tan\beta = 10$

Plots



$M = 400$ TeV, $\tan\beta = 10$

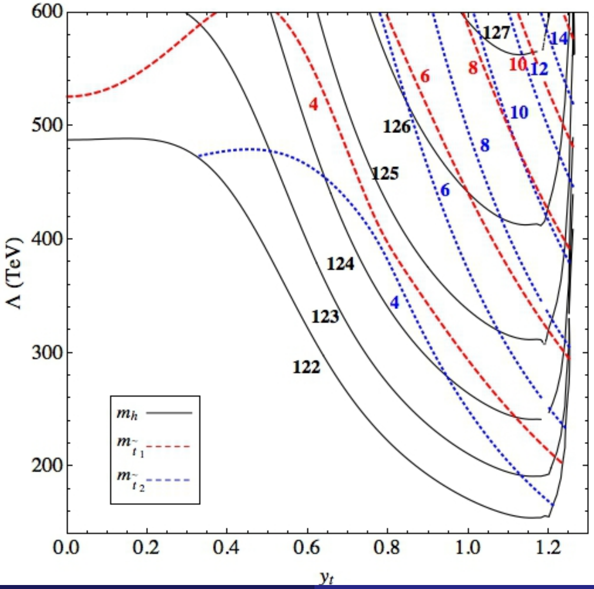
Plots



$M = 10^8$ GeV, $\tan\beta = 20$

- similar to $M = 10^{12}$

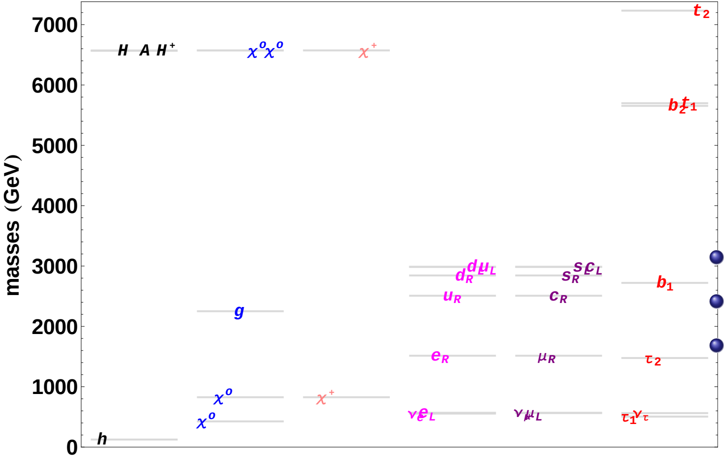
Plots



$M = 10^8$ GeV, $\tan\beta = 20$

- white regions

Example Spectrum



$M = 10^8$ GeV

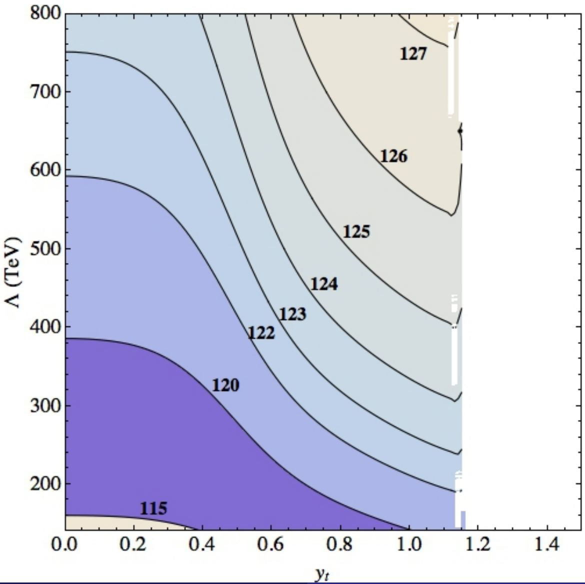
$\Lambda = 3.08$ TeV

$\tan\beta = 20$

$y_t = 1.19$

- $m_{\chi_1^0} = 426$ GeV
- $m_{\tilde{u}_R} = 2508$ GeV
- $m_{\tilde{g}} = 2251$ GeV

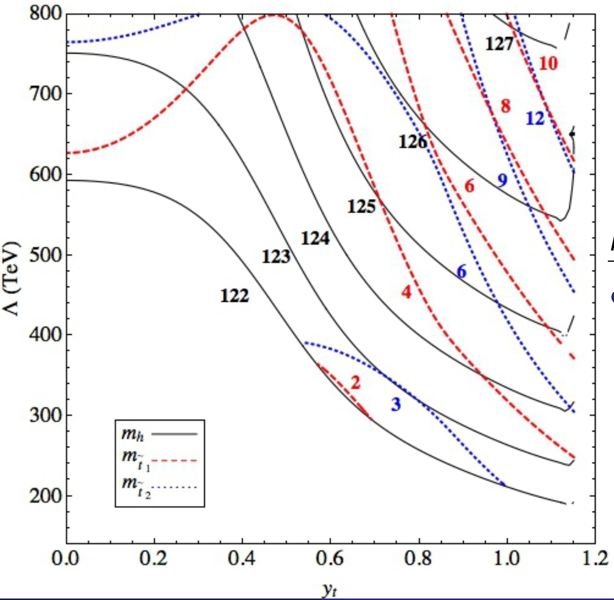
Higgs Mass - Plots



$M = 10^{12}$ TeV, $\tan\beta = 10$

- No tachyonic stops (negative 1-loop is negligible)
- $y_t >\sim 1.2$ get tachyonic staus and problems with EWSB

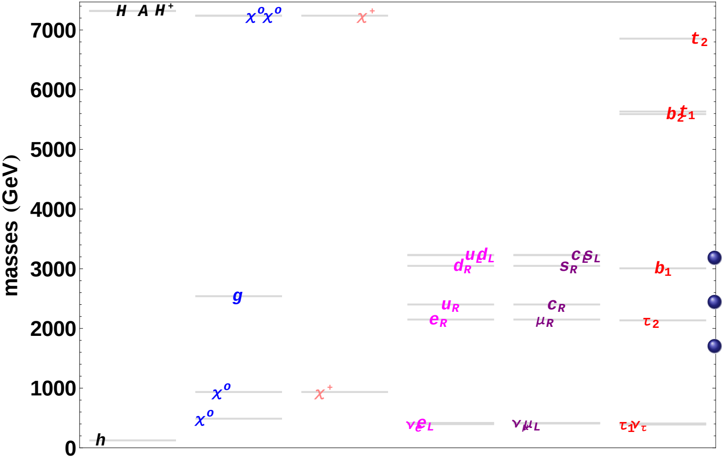
Higgs Mass - Plots



$M = 10^{12}$ TeV, $\tan\beta = 10$

- Need Λ large $\Rightarrow$ heavy spectrum

Higgs Mass - Example Spectrum

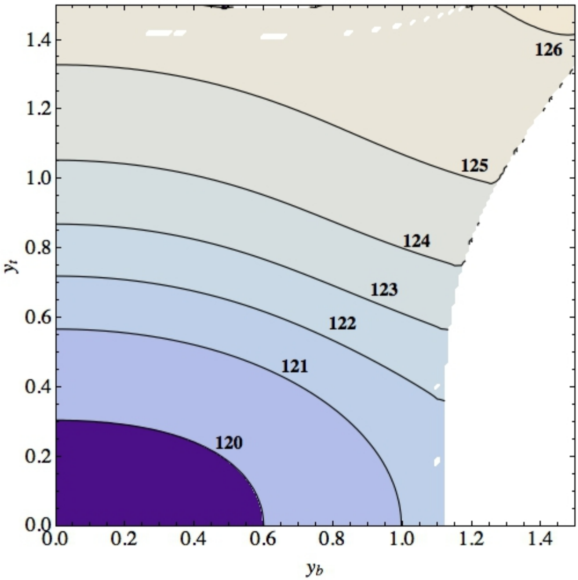


$$M = 10^{12}\ \text{GeV}$$
$$\Lambda = 3.55\ \text{TeV}$$
$$\tan\beta = 10$$
$$y_t = 1.14$$

- $m_{\tau_L} = 390$ GeV
- $m_{\tilde{u}_R} = 2401$ GeV
- $m_{\tilde{g}} = 2540$ GeV

whereas in mGMSB $m_{\tilde{t}_1} \sim 8$ TeV

Higgs Mass - y_t and y_b



$\Lambda = 230$ TeV

$M = 10^8$ GeV

$\tan\beta = 10$

large $y_b \Rightarrow$ Tachyonic $\tilde{l}$

A-terms 3rd-generation limit

$$
\begin{aligned}
A^U_{3,3} &= -\frac{Y_t}{16\pi^2}\left[3y_t^2 + y_b^2\right]\frac{F}{M} \\
A^D_{3,3} &= -\frac{Y_b}{16\pi^2}\left[3y_b^2 + y_t^2\right]\frac{F}{M} \\
A^L_{3,3} &= -\frac{3Y_\tau y_\tau^2}{16\pi^2}\frac{F}{M}
\end{aligned}
$$

and also

$$\delta A^U_{33} = -\frac{1}{16\pi^2} y_t^2 \frac{F^3}{M^5}\,.$$

Soft Squared Masses 3rd-generation limit

$$
\begin{aligned}
\tilde{m}^2_{H_U} &= \tfrac{1}{128\pi^4} \left\{ -\frac{3}{2} Y_t^2 (3y_t^2 + y_b^2) + N \left(\frac{3}{4} g_2^4 + \frac{3}{20} g_1^4 \right) \right\} \left| \frac{F}{M} \right|^2 \\
\tilde{m}^2_{H_D} &= \tfrac{1}{128\pi^4} \left\{ -\frac{3}{2} Y_b^2 (3y_b^2 + y_t^2) - \frac{3}{2} Y_\tau^2 y_\tau^2 + N \left(\frac{3}{4} g_2^4 + \frac{3}{20} g_1^4 \right) \right\} \left| \frac{F}{M} \right|^2 \\
(\tilde{m}^2_q)_{33} &= \tfrac{1}{128\pi^4} \left\{ \left(y_t^2 + 3y_b^2 + 3Y_b^2 + \frac{1}{2} y_\tau^2 - \frac{8}{3} g_3^2 - \frac{3}{2} g_2^2 - \frac{7}{30} g_1^2 \right) y_b^2 \right. \\
&\quad + \left(3y_t^2 + 3Y_t^2 - \frac{8}{3} g_3^2 - \frac{3}{2} g_2^2 - \frac{13}{30} g_1^2 \right) y_t^2 + Y_b y_b Y_\tau y_\tau \\
&\quad \left. + N \left(\frac{4}{3} g_3^4 + \frac{3}{4} g_2^4 + \frac{1}{60} g_1^4 \right) \right\} \left| \frac{F}{M} \right|^2 \\
(\tilde{m}^2_{u^c})_{33} &= \tfrac{1}{128\pi^4} \left\{ \left(6y_t^2 + y_b^2 + Y_b^2 + 6Y_t^2 - \frac{16}{3} g_3^2 - 3g_2^2 - \frac{13}{15} g_1^2 \right) y_t^2 - Y_t^2 y_b^2 \right. \\
&\quad \left. + N \left(\frac{4}{3} g_3^4 + \frac{4}{15} g_1^4 \right) \right\} \left| \frac{F}{M} \right|^2
\end{aligned}
$$

Soft Squared Masses 3rd-generation limit

$$
\begin{aligned}
(\tilde{m}^2_{d^c})_{33} &= \tfrac{1}{128\pi^4} \Bigg\{ \left(6y_b^2 + y_\tau^2 + y_t^2 + Y_t^2 + 6Y_b^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{7}{15}g_1^2\right) y_b^2 \\
&\quad - y_t^2 Y_b^2 + 2Y_b y_b Y_\tau y_\tau + N\left(\frac{4}{3}g_3^4 + \frac{1}{15}g_1^4\right) \Bigg\} \left|\frac{F}{M}\right|^2 , \\
(\tilde{m}^2_{l})_{33} &= \tfrac{1}{128\pi^4} \Bigg\{ \left(\frac{3}{2}y_b^2 + 2y_\tau^2 - \frac{3}{2}g_2^2 - \frac{9}{10}g_1^2\right) y_\tau^2 + \left(Y_\tau^2 y_\tau^2 + 3Y_b y_b Y_\tau y_\tau\right) \\
&\quad + N\left(\frac{3}{4}g_2^4 + \frac{3}{20}g_1^4\right) \Bigg\} \left|\frac{F}{M}\right|^2 \\
(\tilde{m}^2_{e^c})_{33} &= \tfrac{1}{128\pi^4} \Bigg\{ \left(3y_b^2 + 4y_\tau^2 - 3g_2^2 - \frac{9}{5}g_1^2\right) y_\tau^2 + \left(2Y_\tau^2 y_\tau^2 + 6Y_b y_b Y_\tau y_\tau\right) + \frac{3}{5}N g_1^4 \Bigg\} \left|\frac{F}{M}\right|^2 .
\end{aligned}
$$

1-Loop Soft Squared Masses

$$
\begin{aligned}
\delta m^2_{q_L} &= -\frac{1}{(4\pi)^2}\frac{1}{6}\left(y_u y_u^\dagger + y_d y_d^\dagger\right)\frac{F^4}{M^6} \\
\delta m^2_{u_R} &= -\frac{1}{(4\pi)^2}\frac{1}{3}\left(y_u^\dagger y_u\right)\frac{F^4}{M^6} \\
\delta m^2_{d_R} &= -\frac{1}{(4\pi)^2}\frac{1}{3}\left(y_d^\dagger y_d\right)\frac{F^4}{M^6} \\
\delta m^2_{l} &= -\frac{1}{(4\pi)^2}\frac{1}{6}\left(y_l y_l^\dagger\right)\frac{F^4}{M^6} \\
\delta m^2_{e^c} &= -\frac{1}{(4\pi)^2}\frac{1}{3}\left(y_l^\dagger y_l\right)\frac{F^4}{M^6} .
\end{aligned}
$$

A-terms

A-term are the coefficients in

$$L \supset (A_u)_{i,j}\tilde{q}_{Li}\tilde{u}^*_{Rj}H_U + (A_d)_{i,j}\tilde{q}_{Li}\tilde{d}^*_{Rj}H_d + (A_l)_{i,j}\tilde{L}_{Li}\tilde{e}^*_{Rj}H_d$$

$$\begin{aligned}
A_u^* &= -\frac{1}{16\pi^2}\left[\left(y_u y_u^\dagger + y_d y_d^\dagger\right) Y_u + 2Y_u\left(y_u^\dagger y_u\right)\right]\frac{F}{M} \\
A_d^* &= -\frac{1}{16\pi^2}\left[\left(y_u y_u^\dagger + y_d y_d^\dagger\right) Y_d + 2Y_d\left(y_d^\dagger y_d\right)\right]\frac{F}{M} \\
A_l^* &= -\frac{1}{16\pi^2}\left[\left(y_l y_l^\dagger\right) Y_l + 2Y_l\left(y_l^\dagger y_l\right)\right]\frac{F}{M}
\end{aligned}$$

Soft Mass - y_u only

$$\delta\tilde{m}_q^2 = -\frac{1}{(4\pi)^2}\frac{1}{6}\left(y_u y_u^\dagger\right)\frac{F^4}{M^6}h(x) + \frac{1}{(4\pi)^4}\Big\{ \left(3\,Tr\left(y_u^\dagger y_u\right) - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right) y_u y_u^\dagger + 3y_u y_u^\dagger y_u y_u^\dagger + 2y_u Y_u^\dagger Y_u y_u^\dagger - 2Y_u y_u^\dagger y_u Y_u^\dagger + y_u Y_u^\dagger\,Tr\left(3y_u^\dagger Y_u\right) + Y_u y_u^\dagger\,Tr\left(3Y_u^\dagger y_u\right) \Big\}\left|\frac{F}{M}\right|^2,$$

$$\delta\tilde{m}_{u_R}^2 = -\frac{1}{(4\pi)^2}\frac{1}{3}\left(y_u^\dagger y_u\right)\frac{F^4}{M^6}h(x) + \frac{1}{(4\pi)^4}\Big\{ 2\left(3\,Tr\left(y_u^\dagger y_u\right) - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right) y_u^\dagger y_u + 6y_u^\dagger y_u y_u^\dagger y_u + 2y_u^\dagger Y_u Y_u^\dagger y_u + 2y_u^\dagger Y_d Y_d^\dagger y_u - 2Y_u^\dagger y_u y_u^\dagger Y_u + 2y_u^\dagger Y_u\,Tr\left(3Y_u^\dagger y_u\right) + 2Y_u^\dagger y_u\,Tr\left(3y_u^\dagger Y_u\right) \Big\}\left|\frac{F}{M}\right|^2,$$

$$\delta\tilde{m}_{d_R}^2 = -\frac{1}{(4\pi)^4}2Y_d^\dagger y_u y_u^\dagger Y_d\left|\frac{F}{M}\right|^2.$$

FGM: Model Symmetries

Superfield	R-parity	Z_3
X	even	1
D_1	even	0
$\bar{D}_1$	even	-1
D_2	even	-1
$\bar{D}_2$	even	0
$T_I, \bar{T}_I, D_{I>2}, \bar{D}_{I>2}$	even	1
q, u^c, d^c, l, e^c	odd	0
H_U, H_D	even	0

Shadmi & Szabo arXiv:1103.0292

- $N_5 \geq 2$ for: y^U and y^D, y^L

$$W = X(\bar{T}_i T_i + \bar{D}_i \bar{D}_i) + Y^u Q H^u u^c + Y^d Q H^d d^c + Y^l L H^d e^c$$
$$+ y^u Q \bar{D}_1 u^c + y^d Q D_2 d^c + y^l L D_2 e^c$$