Flavoring GMSB - Non-Degenerate Squarks and a Heavy Higgs in Flavored GMSB

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

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Outline

1. Motivation: Flavor $\Longleftrightarrow$ SUSY $\Longleftrightarrow$ Higgs
2. Messenger - Matter couplings: Flavored Gauge Mediation(FGM)
3. Non-degenerate squarks
4. A heavy Higgs (with interesting spectra)
5. Analytic Continuation into Superspace and soft terms calculation
6. Conclusions and outlook

Motivation: SM Flavor Puzzle & New Physics

SM Flavor Puzzle

- $m_e : m_\mu : m_\tau \approx 1 : 200 : 4,000$
- $m_d : m_s : m_b \approx 1 : 30 : 4,000$
- $m_u : m_c : m_t \approx 1 : 1,000 : 200,000$
- $V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$ $\quad \begin{matrix} \lambda \sim 0.22 \\ A \sim 0.81 \\ \rho \sim 0.13 \\ \eta \sim 0.35 \end{matrix}$

very non trivial structure

How should the new physics flavor structure look like ?

Theory of flavor for SM $\Longrightarrow$ Automatically explains new physics flavor structure (soft terms)

Motivation: The Higgs Boson

Pretty clear we found a

Higgs boson

$$m_h = 125.9 \pm 0.4 \text{ GeV (PDG)}$$

$\Longrightarrow$

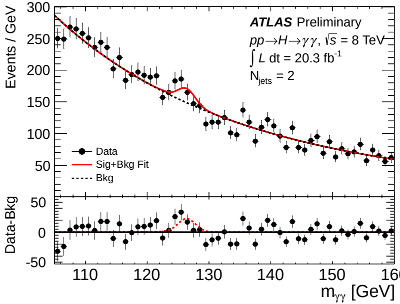


figure from: ATLAS-CONF-2013-072

Motivation: The Higgs Mass in The MSSM

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 $m_h \sim 126$ GeV

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

In GMSB

For GMSB (and General Gauge Mediation (GGM))

- RG $\Longrightarrow$ generates A-terms (zero at messenger scale)
- $M_{\tilde{g}} \Longrightarrow$ Running of A-terms and $m^2_{\tilde{t}}$

To realize $m_h \sim 126$ GeV with GMSB

1. a high messenger scale
2. heavy squarks & heavy gluinos

e.g Feng, Surujon & Yu

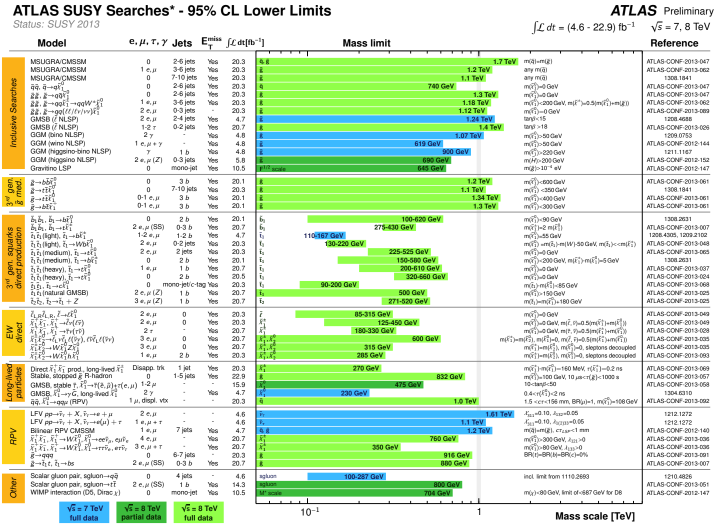
for GGM, Draper, Meade, Reece & Shih

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

for 3-loops see Feng, Kant, Profumo & Sanford

Motivation: SUSY Searches @ The LHC

So far: No light, flavor-blind superpartners



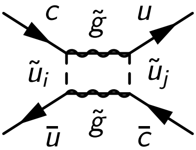
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

One common assumption in SUSY searches

The superpartner spectrum is flavor-blind

Flavor Issues

Low-E observables constrain the SUSY flavor structure



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

- Degeneracy
- Alignment
- Decoupling

In many SUSY models

Minimal Flavor Violation

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

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

Simplest searches: Jets + $\not{E}_T$

Rough bounds:

$$m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 1.7\ \mathrm{TeV(CMSSM)}$$

Flavor in SUSY searches

But in fact

MFV is over constraining

sfermions can have mass splittings and/or mixing

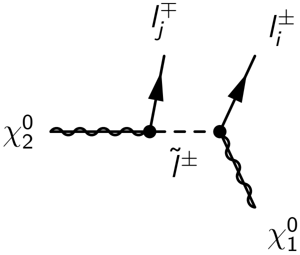
bounds on $\delta_{ij} = \frac{(\Delta\tilde{m}^2)_{ij}\ K_{ij}}{\bar{m}^2}$ allow: small mixing $\Leftrightarrow$ large splitting

Flavor Effects

If the flavor structure of superpartners is non-trivial

- previously unavailable channels might lead to new signals
- techniques designed to find the signatures of flavor-blind spectra may become inefficient

Example 1: $\tilde{\chi}_2^0 \to \tilde{l}^\pm l_j^\mp \to \tilde{\chi}_1^0 l_j^\mp l_i^\pm$



Galon & Shadmi arXiv:1108.2220 [hep-ph]

Di-lepton endpoint

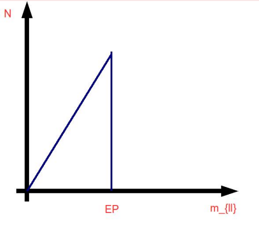
$$m_{ll}^2\big|_{endpoint} = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}}^2}$$

No Flavor

- degeneracy $m_{\tilde{e}} = m_{\tilde{\mu}}$
- no mixing
- signal in $ee, \mu\mu$ distribution
- No signal in $e\mu$ distribution

No Flavor

For $ee, \mu\mu$



Example 1: $\tilde{\chi}_2^0 \to \tilde{l}^{\pm} l_j^{\mp} \to \tilde{\chi}_1^0 l_j^{\mp} l_i^{\pm}$

With Flavor

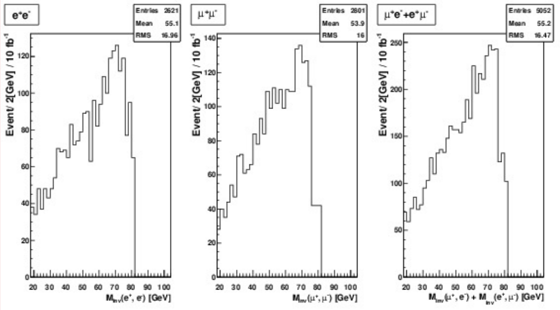
Mixing

$$\begin{pmatrix} \tilde{l}_1 \\ \tilde{l}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{e} \\ \tilde{\mu} \end{pmatrix}$$

Splitting

$$\tilde{m}_2 = \tilde{m}_1 + \Delta m$$

With Flavor



In the flavored case

- Cannot use "Flavor Subtraction": $ee + \mu\mu - e\mu - \mu e$
- Cannot enhance the slepton signal see Eckel, Shepherd & Su

Example 2: Squark Mass Bounds

Simplified Models (and the resulting bounds)

assume 8-fold squark degeneracy

non-MFV Squarks at LHC searches

Production: X-sections affected by non-degenerate 1^{st} 2^{nd} gen squarks - mainly sensitive to u, d PDFs (for non-decoupled gluinos)

Detection:

- lighter squarks: efficiency reduced (e.g light $\tilde{c}_R$)
  Mahbubani, Papucci, Perez, Ruderman & Weiler
- mixings affect detection (especially for $\tilde{t}, \tilde{b}, \tilde{c}$)
  Blanke, Giudice, Paradisi, Perez & Zupan , Agrawal & Frugiuele

Extend: GMSB

$\Downarrow$

Flavored GMSB (FGM)

$\Longrightarrow$

Gauge Mediated SUSY Breaking (GMSB)

The (minimal) GMSB superpotential

Dine, Nelson & Shirman

Dine, Nelson, Nir & Shirman

$$W = X\phi\bar{\phi} + Y^u Q H^u u^c + Y^d Q H^d d^c + Y^l L H^d e^c$$

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

Coupling to Messengers

$5 + \bar{5}$ of $SU(5)$ messengers

$$\phi_i = \begin{pmatrix} T \\ \bar{D} \end{pmatrix} \qquad \bar{\phi}_i = \begin{pmatrix} \bar{T} \\ D \end{pmatrix}$$

In general

- Messenger can couple to visible fields in various ways

$$D \Leftrightarrow H_d, L, \qquad \bar{D} \Leftrightarrow H_u,$$

- need a mechanism (symmetry, 5d construction) to prevent them from coupling to matter Dine, Nir & Shirman Dvali, Giudice & Pomarol Chacko & Ponton

Schematics

Yukawa-like messenger-matter couplings

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

Upshot

flavor dependent

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

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

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

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

Soft Terms

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)

$$\tilde{m}^2 \sim -\frac{y^2}{(4\pi)^2}\frac{F^4}{M^6}$$

Flavor Structure

SM flavor structure

$$Y_u, Y_d, Y_l \iff \begin{matrix} \{m_e & m_\mu & m_\tau\} \\ \{m_d & m_s & m_b\}, \\ \{m_u & m_c & m_t\} \end{matrix} \quad V_{CKM}$$

Messenger flavor structure

$$y_u, \; y_d, \; y_l$$

Add a flavor theory

- Explain SM mass hierarchies & mixings within the flavor theory

  Automatically
- same flavor theory controls new couplings

non-degenerate squarks

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

$\Longrightarrow$

Flavor Symmetry

Flavor symmetry (say $U(1)$) is broken by a spurion $\lambda(-1)$

$$\lambda \sim 0.2$$

Higher-dim operators

$$W \supset CQH^u u^c (\lambda)^n + C' Q\bar{D}u^c (\lambda)^{n'} + \dots$$

and n, n' = sum of charges

Froggatt-Nielsen

$$Y \sim \begin{cases} C\lambda^n & n \geq 0 \\ 0 & n < 0 \end{cases} \implies$$

$y = C'\lambda^{n'}$

- $n' = n \implies Y \sim y$ MFV
- $n' > n \implies Y > y$ suppressed
- $n' < n \implies Y < y$ interesting

Flavor Symmetry

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

Charges, borrowing from 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}

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

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

Flavor Symmetry

Assigning messenger charges

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

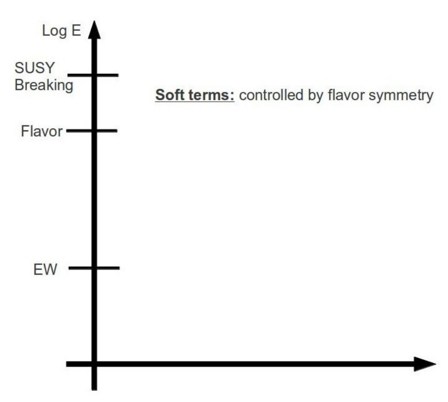
determines the pattern of

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

we will choose n, m 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

Usual Alignment

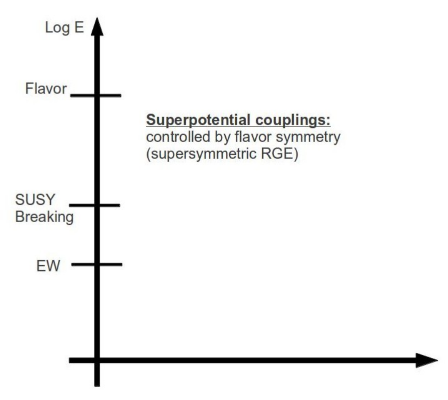


Nir & Seiberg

- aligned **soft terms** - above the flavor symmetry scale
- $\Longrightarrow$ must be **high scale** ~~SUSY~~
- RGE: **mild splittings**

Supersymmetric Alignment

Supersymmetric Alignment



Shadmi & Szabo

- aligned **superpotential couplings**
- can be **low-scale** $\not{SUSY}$
- soft-terms "inherit" structure
- RGE: **large splittings**

Non-Degenerate Squarks

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

Choose (m, n) such that

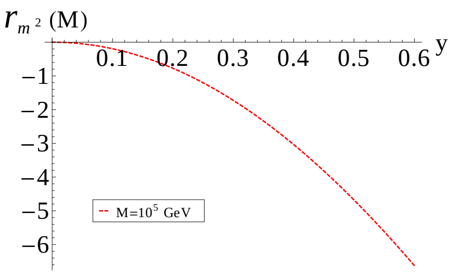
$$(y_u)_{ij} \approx y\delta_{i2}\delta_{j2}$$

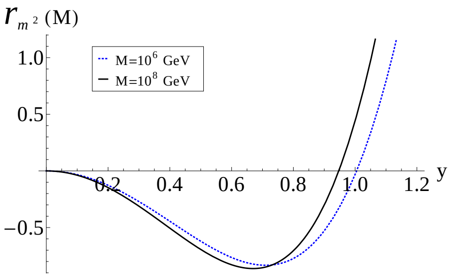
$\Longrightarrow$

Then

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

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





Phenomenology

Light charm- and strange-squarks

$$\underline{D(-1,3),\ \bar{D}(1,-3)} \Longrightarrow y_u \sim \begin{pmatrix} \lambda^4 & 0 & 0 \\ 0 & c_{22}\lambda & 0 \\ 0 & 0 & 0 \end{pmatrix} \Longrightarrow (\delta\tilde{m}_{Q_L}, \delta\tilde{m}_{U_R})_{22}$$

Heavy up- and down-squarks

$$\underline{D(0,6),\ \bar{D}(0,-6)} \Longrightarrow y_u \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \Longrightarrow (\delta\tilde{m}_{Q_L}, \delta\tilde{m}_{U_R})_{11}$$

Notice the Holomorphic zeros

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), $\tan\beta = 5)$ - Massless $\tilde{c}_R$ $\mu = M$

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

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

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
- ...

$\Longrightarrow$

MFV-like FGM

so for $m_h \approx 126$ 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 charges

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

Main Features

$$W = X(\bar{T}_i T_i + \bar{D}_i D_i) \quad + \quad Y^u Q H_u u^c + Y^d Q H_d d^c + Y^l L H_d e^c$$
$$+ \quad y Q_3 \bar{D} t^c$$

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)
$$\tilde{m}^2 \sim -\frac{y^2}{(4\pi)^2}\frac{F^4}{M^6}$$

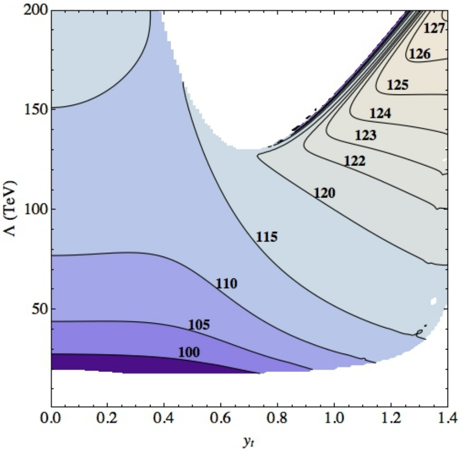
Higgs mass

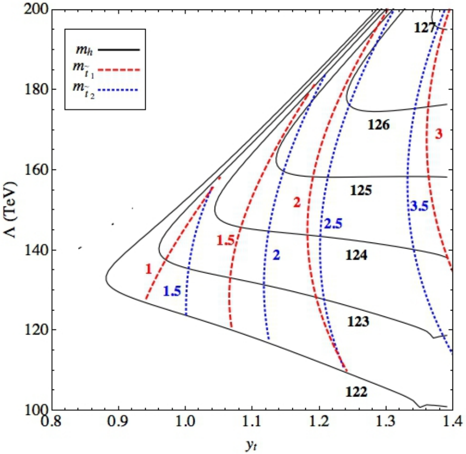
Two possibilities for Higgs mass

- mostly stop A-terms, LL, RR $\pm$ contributions cancel (1-loop: mainly low scales): light spectra.
- enhanced by the large LL,RR stop masses - heavy stops

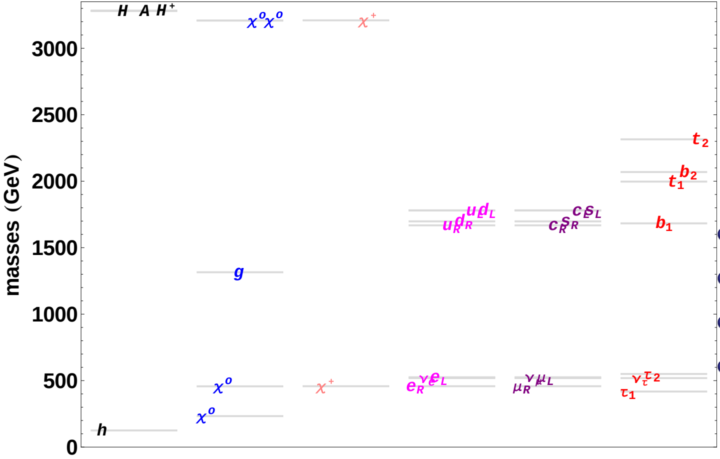
MFV-like: Heavy Higgs & $\sim$ TeV Spectra

$A_{33}, \tilde{m}^2_{33}$ $\Longrightarrow$ $M = 400$ TeV, $\tan\beta = 10$





Example Spectrum



$$M = 400 \text{ TeV}$$

$$\Lambda = 165 \text{ TeV}$$

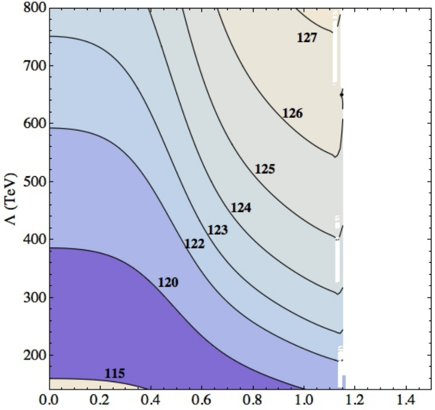
$$\tan\beta = 10$$

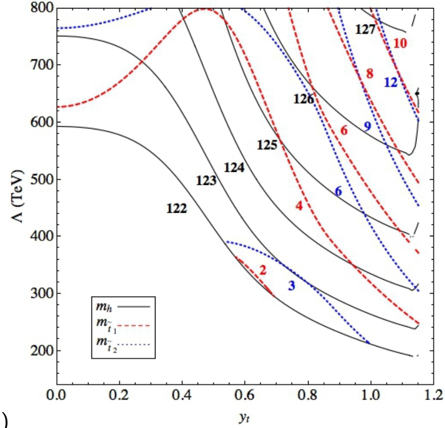
$$y_t = 1.2$$

- $m_{\chi^0} = 233$ GeV
- $m_{\tilde{q}} \sim 1.7$ TeV
- $m_{\tilde{g}} \sim 1.3$ TeV
- $m_{\tilde{t}_1} \sim 2$ TeV

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

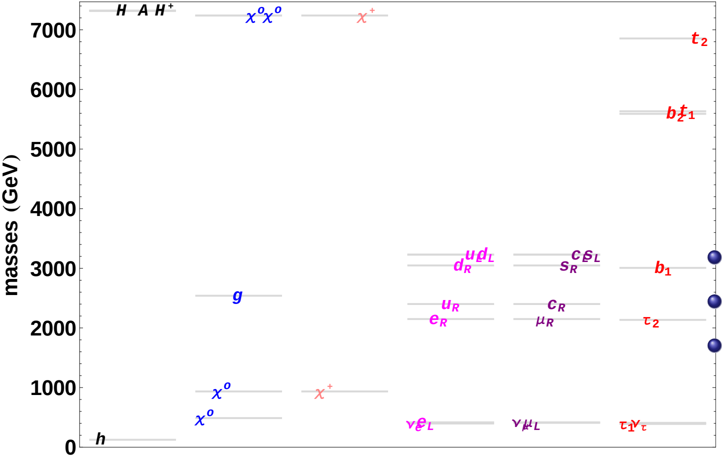
$A_{33}, \tilde{m}^2_{33}$ $\Longrightarrow$ $M = 10^{12}$ TeV, $\tan\beta = 10$





- No tachyonic stops (negative 1-loop is negligible)
- $y_t \gtrsim 1.2 \to$ tachyonic staus, EWSB problems
- Need Λ large ⇒ heavy spectrum

Example Spectrum



$M = 10^{12}$ GeV

$\Lambda = 355$ 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

heavy split stops affect the RG evolution: can lead to interesting spectra

A Heavy Higgs & Non-Degenerate Squarks

Choose flavor charges

$$\underline{D(-2,3),\ \bar{D}(2,3)}$$

Then

$$y_u \sim \begin{pmatrix} \lambda^5 & 0 & 0 \\ 0 & \lambda^2 & 0 \\ 0 & y & 0 \end{pmatrix} \Longrightarrow$$

- Soft masses:

$$(\delta\tilde{m}_{u_R})_{22},\ (\delta\tilde{m}_{u_R})_{33},\ (\delta\tilde{m}_{Q_L})_{33}$$

- A-terms:

$$A_t \sim \frac{1}{16\pi^2}|y^2|Y_t$$

A non-degenerate squarks, and a heavy Higgs and new stop mass contributions.

Analytic Continuation into Superspace and calculation of soft terms

$\Longrightarrow$

Calculation of Soft Terms

Analytic Continuation into superspace

$\not{SUSY}$ enters through $Z(X^\dagger, X, \mu)$

$$Z|_{X=M+\theta^2 F} = Z + \frac{\partial Z}{\partial X}\theta^2 F + \frac{\partial Z}{\partial X^\dagger}\theta^2 F^\dagger \frac{\partial^2 Z}{\partial X^\dagger \partial X}\theta^4 F^\dagger F$$

Expanding

$$\int d^4\theta \phi^\dagger Z \phi \qquad \Longrightarrow \qquad m^2_{\tilde{\phi}} = -\frac{\partial^2 \ln Z}{\partial(\ln X^\dagger)\partial(\ln X)} \frac{F^\dagger F}{M^\dagger M}$$

Giudice & Rattazzi

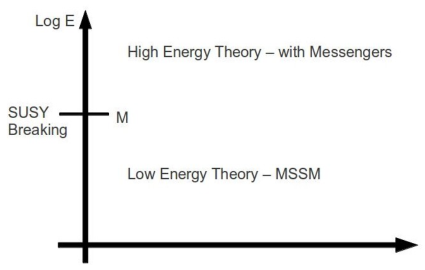
Arkani-Hamed, Giudice, Luty & Rattazzi

The key: identify $M = \sqrt{X^\dagger X}$

$$m^2_{\tilde{\phi}} = -\frac{1}{4}\frac{\partial^2 \ln Z}{\partial(\ln M)^2}\left|\frac{F}{M}\right|^2$$

Calculation of Soft Terms

Schematically



Analytic Continuation

- Integrate out messenger
- leading F/M soft terms
- Running

$$\frac{d \ln Z}{d \ln \mu} = \gamma(\lambda), \ \frac{d\lambda}{d \ln \mu} = \beta$$

Calculation of Soft Terms

see Chacko & Ponton

$$\ln Z_\phi(\mu < M) = \int_{\ln\Lambda}^{\ln M} \gamma^> d(\ln\mu') + \int_{\ln M}^{\ln\mu} \gamma^< d(\ln\mu')$$

$$\left.\frac{d\ln Z_\phi}{d(\ln M)}\right|_{\mu=M} = \Delta\gamma(M)$$

$$\left.\frac{d^2\ln Z_\phi}{d(\ln M)^2}\right|_{\mu=M} = \frac{d\Delta\gamma(M)}{d(\ln M)} - \left.\frac{d\gamma^<(\mu)}{d(\ln M)}\right|_{\mu=M}$$

$$\lambda(\mu < M) = \lambda(\Lambda) + \int_{\ln\Lambda}^{\ln M} \beta^> d(\ln\mu') + \int_{\ln M}^{\ln\mu} \beta^< d(\ln\mu')$$

$$m_{\tilde\phi}^2 = -\left[\sum_\lambda \frac{\partial\Delta\gamma_\phi}{\partial\lambda}\beta_\lambda^> - \frac{\partial\gamma_\phi^<}{\partial\lambda}\Delta\beta_\lambda\right]\left|\frac{F}{M}\right|^2$$

Calculation of Soft Terms

Must be done carefully:

multiple fields

$$\frac{dZ}{d \ln \mu} = Z^{1/2} \gamma Z^{1/2}$$

Kinetic mixing at 1-loop $\Longrightarrow \tilde{m}^2|_{2-loop}$

Calculation of Soft Terms

Simplified Model - High-E theory

Superpotential $$W = X\bar{D}D + Y^0 Hle + y^0 Dle$$

Kinetic terms

$$\int d^4\theta \begin{pmatrix} D^\dagger & H^\dagger \end{pmatrix} \begin{pmatrix} Z_{DD} & Z_{DH} \\ Z_{HD} & Z_{HH} \end{pmatrix} \begin{pmatrix} D \\ H \end{pmatrix} = \int d^4\theta \ \phi_i^\dagger Z_{i,j} \phi_j$$

and assume $Z_{i,j}(\mu = \Lambda) = \delta_{i,j}$

Simplified Model - Low-E theory

Kinetic term,

$$\int d^4\theta \ h^\dagger Z_h h,$$

Superpotential

$$W = Y_h^0 hle$$

Calculation of Soft Terms

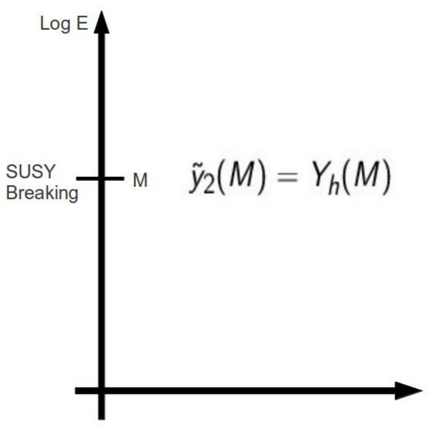
Things to note:

- Calculating $\tilde{m}^2\Big|_{2-loop}$ - must account for 1-loop effects.
- physical states @ 1-loop ?
- associated physical coupling $\tilde{y}_j$?
- RG running: $\gamma^>, \gamma^<, \Delta\gamma$?

Need to match theories at the boundary $M|_{1-loop}$

Calculation of Soft Terms

Match couplings at boundary



Implications

- $Z_h = Z_{22}$ (1-loop)
- Determines RG at low-E
- modifications $\sim \gamma_{12}$

Bottom line

- $\gamma_l^< \sim \tilde{y}_2^2$ and $\Delta\gamma_l = \tilde{y}_1^2$
- $\gamma_h^< \sim \tilde{y}_2^2$ and $\Delta\gamma_h \neq 0$
- Higgs: unchanged
- Matter: receive $\sim |yY|^2$

Conclusions and Outlook

- 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 126 GeV Higgs mass with superpartners accessible at the LHC
- FGM models lead to interesting squark and slepton masses
- Flavorful spectra - need new LHC search strategies

Thank You

Backup Slides

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

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

Bounds On δs

$$(\delta^q_{ij})_{MM} = \frac{\Delta\tilde{m}^2_{q_j q_i}}{\tilde{m}^2_q}(K^q_M)_{ij}(K^q_M)^*_{jj},$$

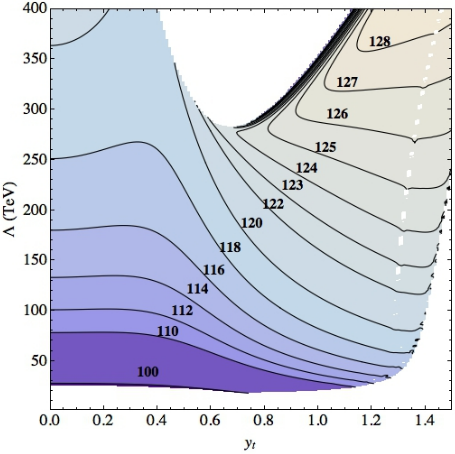
where $\Delta\tilde{m}^2_{q_j q_i} = m^2_{q_j} - m^2_{q_i}$, and $\tilde{m}^2_q$

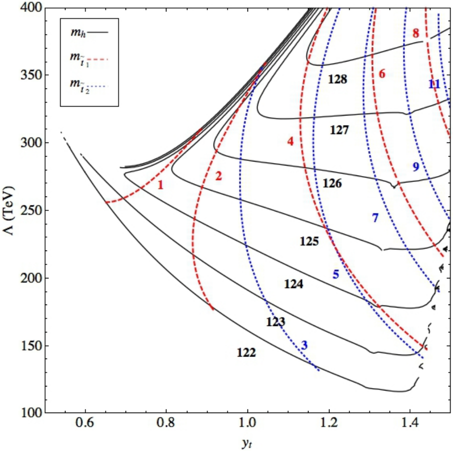
q	ij	$\lvert(\delta^q_{ij})_{MM}\rvert$	$\sqrt{\mathrm{Im}(\delta^q_{ij})^2_{MM}}$	$\sqrt{\mathrm{Im}((\delta^q_{ij})_{LL}(\delta^q_{ij})_{RR})}$
d	12	0.07	0.01	0.0005
u	12	0.1	0.05	0.003
d	23	0.6	0.2	0.07

Table: The upper bounds on $(\delta^q_{ij})_{MM}$, taken from Isidori, Nir & Perez, but assuming order-one phases, for $m_{\tilde{q}} = 1$ TeV and $m_{\tilde{g}}/m_{\tilde{q}} = 1$.

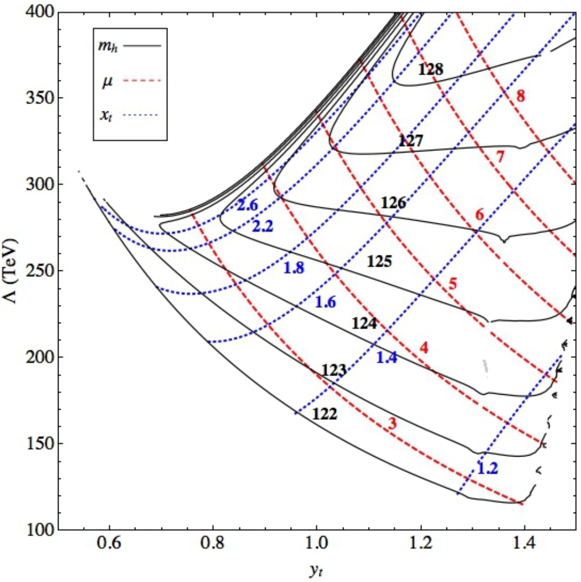
MFV-like: Heavy Higgs & $\sim$ TeV Spectra

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





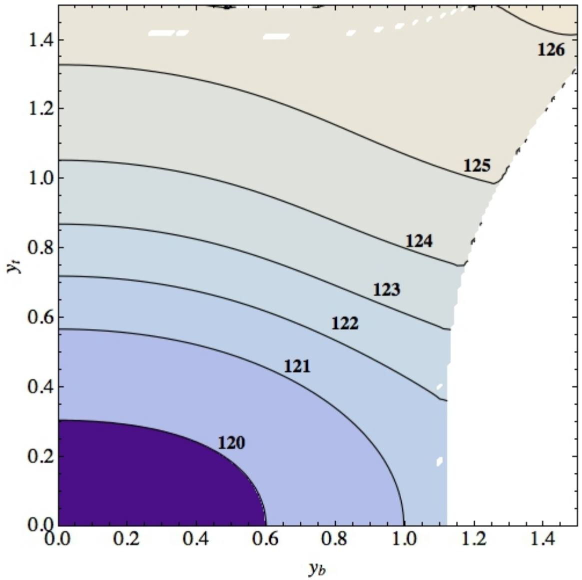
Higgs Mass



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

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

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

$$\tilde{m}^2_{H_U} = \frac{1}{128\pi^4} \left\{ -\frac{3}{2} Y_t^2 (3y_t^2 + y_b^2) + N\left(\frac{3}{4}g_2^4 + \frac{3}{20}g_1^4\right)\right\} \left|\frac{F}{M}\right|^2$$

$$\tilde{m}^2_{H_D} = \frac{1}{128\pi^4} \left\{ -\frac{3}{2} Y_b^2 (3y_b^2 + y_t^2) - \frac{3}{2} Y_\tau^2 y_\tau^2 + N\left(\frac{3}{4}g_2^4 + \frac{3}{20}g_1^4\right)\right\} \left|\frac{F}{M}\right|^2$$

$$(\tilde{m}^2_q)_{33} = \frac{1}{128\pi^4} \left\{ \left(y_t^2 + 3y_b^2 + 3Y_b^2 + \frac{1}{2}y_\tau^2 - \frac{8}{3}g_3^2 - \frac{3}{2}g_2^2 - \frac{7}{30}g_1^2\right) y_b^2 \right.$$
$$+ \left(3y_t^2 + 3Y_t^2 - \frac{8}{3}g_3^2 - \frac{3}{2}g_2^2 - \frac{13}{30}g_1^2\right) y_t^2 + Y_b y_b Y_\tau y_\tau$$
$$\left. + N\left(\frac{4}{3}g_3^4 + \frac{3}{4}g_2^4 + \frac{1}{60}g_1^4\right) \right\} \left|\frac{F}{M}\right|^2$$

$$(\tilde{m}^2_{u^c})_{33} = \frac{1}{128\pi^4} \left\{ \left(6y_t^2 + y_b^2 + Y_b^2 + 6Y_t^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right) y_t^2 - Y_t^2 y_b^2 \right.$$
$$\left. + N\left(\frac{4}{3}g_3^4 + \frac{4}{15}g_1^4\right)\right\} \left|\frac{F}{M}\right|^2$$

Soft Squared Masses 3rd-generation limit

$$(\tilde{m}^2_{d^c})_{33} = \tfrac{1}{128\pi^4} \left\{ \left(6y_b^2 + y_\tau^2 + y_t^2 + Y_t^2 + 6Y_b^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{7}{15}g_1^2\right) y_b^2 \right.$$
$$\left. - y_t^2 Y_b^2 + 2Y_b y_b Y_\tau y_\tau + N\left(\frac{4}{3}g_3^4 + \frac{1}{15}g_1^4\right) \right\} \left|\frac{F}{M}\right|^2 ,$$

$$(\tilde{m}^2_{l})_{33} = \tfrac{1}{128\pi^4} \left\{ \left(\frac{3}{2}y_b^2 + 2y_\tau^2 - \frac{3}{2}g_2^2 - \frac{9}{10}g_1^2\right) y_\tau^2 + \left(Y_\tau^2 y_\tau^2 + 3Y_b y_b Y_\tau y_\tau\right) \right.$$
$$\left. + N\left(\frac{3}{4}g_2^4 + \frac{3}{20}g_1^4\right) \right\} \left|\frac{F}{M}\right|^2$$

$$(\tilde{m}^2_{e^c})_{33} = \tfrac{1}{128\pi^4} \left\{ \left(3y_b^2 + 4y_\tau^2 - 3g_2^2 - \frac{9}{5}g_1^2\right) y_\tau^2 + \left(2Y_\tau^2 y_\tau^2 + 6Y_b y_b Y_\tau y_\tau\right) + \frac{3}{5}Ng_1^4 \right\} \left|\frac{F}{M}\right|^2 .$$

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

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