

Flavoring GMSB - Non-Degenerate Squarks and 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

Nov 7, 2013

Outline

- 1 Motivation: Flavor $\iff$ SUSY $\iff$ 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

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

very non trivial structure

How should the new physics flavor structure look like ?

Theory of flavor for SM



Automatically explains new physics flavor structure (soft terms)

Motivation: The Higgs Boson

Pretty clear we found a

Higgs boson



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

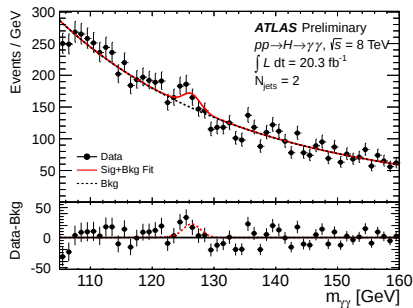


figure from: ATLAS-CONF-2013-072

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

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

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 $\implies$ generates A-terms (zero at messenger scale)
- $M_{\tilde{g}} \implies$ Running of A-terms and $m_{\tilde{t}}^2$

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 $\implies$ 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

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$$\sqrt{s} = 7, 8 \text{ TeV}$$

	Model	e, μ, τ, γ	Jets	$E_{\text{miss}}^{\text{min}}$	$\mathcal{L} \text{ dt} [\text{fb}^{-1}]$	Mass limit	Reference		
Inclusive Searches	MSUGRA/CMSM	0	2-6 jets	Yes	20.3	4.8	1.7 TeV	ATLAS-CONF-2013-047	
	MSUGRA/CMSM	1 e, μ	3-6 jets	Yes	20.3	1.2 TeV	any $m(\tilde{g})$	ATLAS-CONF-2013-062	
	MSUGRA/CMSM	0	7-10 jets	Yes	20.3	1.1 TeV	1308.1841		
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	740 GeV	$m(\tilde{g}) > 0 \text{ GeV}$	ATLAS-CONF-2013-047	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	1.3 TeV	$m(\tilde{g}) > 0 \text{ GeV}$	ATLAS-CONF-2013-047	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0 \rightarrow q\bar{q}W^+W^- \tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	1.16 TeV	$m(\tilde{g}) > 200 \text{ GeV}, m(\tilde{t}) > 0.5(m(\tilde{t}) + m(\tilde{g}))$	ATLAS-CONF-2013-062	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}(t\bar{t}/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	1.16 TeV	$m(\tilde{g}) > 0 \text{ GeV}$	ATLAS-CONF-2013-059	
	GMSB (J NLSIP)	2 e, μ	2-4 jets	Yes	4.7	1.24 TeV	1208.4608		
	GMSB (J NLSIP)	1, 2 τ	0-2 jets	Yes	20.7	1.4 TeV	$m(\tilde{g}) > 50 \text{ GeV}$	ATLAS-CONF-2013-026	
	GGM (bino NLSIP)	2 γ	-	Yes	4.8	1.07 TeV	1209.0753		
	GGM (wino NLSIP)	1 $e, \mu + \tau$	-	Yes	4.8	900 GeV	$m(\tilde{g}) > 50 \text{ GeV}$	ATLAS-CONF-2013-144	
	GGM (higgsino-bino NLSIP)	γ	1 b	Yes	4.8	900 GeV	1211.1167		
	GGM (higgsino NLSIP)	2 $e, \mu (Z)$	0-3 jets	Yes	5.8	890 GeV	$m(\tilde{g}) > 200 \text{ GeV}$	ATLAS-CONF-2012-152	
	Gravitino LSP	0	mono-jet	Yes	10.5	845 GeV	$m(\tilde{g}) > 16^{-1} \text{ eV}$	ATLAS-CONF-2012-147	
3 γ gen, 2 med.	$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	1.2 TeV	$m(\tilde{g}) > 800 \text{ GeV}$	ATLAS-CONF-2013-061	
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	1.1 TeV	$m(\tilde{g}) > 350 \text{ GeV}$	1308.1841	
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	1.34 TeV	$m(\tilde{g}) > 400 \text{ GeV}$	ATLAS-CONF-2013-061	
	$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	1.3 TeV	$m(\tilde{g}) > 300 \text{ GeV}$	ATLAS-CONF-2013-061	
3 γ gen, squarks direct production	$\tilde{u}_L\tilde{u}_L \rightarrow t\bar{t}\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$m(\tilde{g}) > 30 \text{ GeV}$	1308.2631		
	$\tilde{u}_L\tilde{u}_L \rightarrow t\bar{t}\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 b	Yes	20.7	275-430 GeV	$m(\tilde{g}) > 30 \text{ GeV}$	ATLAS-CONF-2013-007	
	$\tilde{u}_L\tilde{u}_L \text{ (light)} \rightarrow b\bar{b}\tilde{\chi}_1^0$	1-2 e, μ	1-2 b	Yes	4.7	110-187 GeV	$m(\tilde{g}) > 55 \text{ GeV}$	1208.4305, 1209.2102	
	$\tilde{u}_L\tilde{u}_L \text{ (light)} \rightarrow b\bar{b}\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	130-320 GeV	$m(\tilde{g}) > 1 \text{ GeV}, m(W) > 50 \text{ GeV}, m(\tilde{g}) > m(\tilde{g})$	ATLAS-CONF-2013-048	
	$\tilde{u}_L\tilde{u}_L \text{ (medium)} \rightarrow t\bar{t}\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	225-525 GeV	$m(\tilde{g}) > 100 \text{ GeV}, m(\tilde{g}) > 50 \text{ GeV}$	ATLAS-CONF-2013-055	
	$\tilde{u}_L\tilde{u}_L \text{ (medium)} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0	2 b	Yes	20.1	150-580 GeV	$m(\tilde{g}) > 300 \text{ GeV}$	1308.2631	
	$\tilde{u}_L\tilde{u}_L \text{ (heavy)} \rightarrow t\bar{t}\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	200-610 GeV	$m(\tilde{g}) > 0 \text{ GeV}$	ATLAS-CONF-2013-037	
	$\tilde{u}_L\tilde{u}_L \text{ (heavy)} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0	2 b	Yes	20.5	320-660 GeV	$m(\tilde{g}) > 0 \text{ GeV}$	ATLAS-CONF-2013-024	
	$\tilde{u}_L\tilde{u}_L \rightarrow t\bar{t}\tilde{\chi}_1^0$	0	mono-jet+tag	Yes	20.3	50-200 GeV	$m(\tilde{g}) > 85 \text{ GeV}$	ATLAS-CONF-2013-058	
	$\tilde{u}_L\tilde{u}_L \text{ (natural GMSB)}$	2 $e, \mu (Z)$	1 b	Yes	20.7	500 GeV	$m(\tilde{g}) > 150 \text{ GeV}$	ATLAS-CONF-2013-025	
	$\tilde{u}_L\tilde{u}_L \rightarrow t\bar{t}\tilde{\chi}_1^0 + Z$	3 $e, \mu (Z)$	1 b	Yes	20.7	271-520 GeV	$m(\tilde{g}) > 170 \text{ GeV}$	ATLAS-CONF-2013-025	
	EW direct	$\tilde{t}_L\tilde{t}_L \rightarrow t\bar{t}\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	85-315 GeV	$m(\tilde{g}) > 0 \text{ GeV}$	ATLAS-CONF-2013-049
		$\tilde{t}_L\tilde{t}_L \rightarrow t\bar{t}\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	203 GeV	$m(\tilde{g}) > 0 \text{ GeV}, m(\tilde{g}) > 0.5 m(\tilde{g}) + m(\tilde{g})$	ATLAS-CONF-2013-049
		$\tilde{t}_L\tilde{t}_L \rightarrow t\bar{t}\tilde{\chi}_1^0$	2 τ	-	Yes	20.7	180-330 GeV	$m(\tilde{g}) > 0 \text{ GeV}, m(\tilde{g}) > 0.5 m(\tilde{g}) + m(\tilde{g})$	ATLAS-CONF-2013-028
$\tilde{t}_L\tilde{t}_L \rightarrow t\bar{t}\tilde{\chi}_1^0$		3 e, μ	0	Yes	20.7	600 GeV	$m(\tilde{g}) > 0 \text{ GeV}, m(\tilde{g}) > 0.5 m(\tilde{g}) + m(\tilde{g})$	ATLAS-CONF-2013-035	
$\tilde{t}_L\tilde{t}_L \rightarrow W\tilde{\chi}_1^0 Z$		3 e, μ	0	Yes	20.7	315 GeV	$m(\tilde{g}) > 0 \text{ GeV}, m(\tilde{g}) > 0.5 m(\tilde{g}) + m(\tilde{g})$	ATLAS-CONF-2013-035	
$\tilde{t}_L\tilde{t}_L \rightarrow W\tilde{\chi}_1^0 Z$		1 e, μ	2 b	Yes	20.3	295 GeV	$m(\tilde{g}) > 0 \text{ GeV}, m(\tilde{g}) > 0.5 m(\tilde{g}) + m(\tilde{g})$	ATLAS-CONF-2013-035	
Long-lived particles		Direct $\tilde{t}_L\tilde{t}_L$ prod., long-lived $\tilde{\chi}_1^0$	Disapp. brik	1 jet	Yes	20.3	270 GeV	$m(\tilde{g}) > 160 \text{ MeV}, m(\tilde{g}) > 0.2 m$	ATLAS-CONF-2013-059
		Stable, stopped $\tilde{t}_L$ hadron	0	1-6 jets	Yes	22.9	475 GeV	$m(\tilde{g}) > 105 \text{ GeV}, 10 \text{ pb} < \sigma(\tilde{g}) < 1000 \text{ s}$	ATLAS-CONF-2013-057
		CMSB, stable $\tilde{t}_L$, $\tilde{t}_L \rightarrow \tilde{t}(\tilde{g})\tilde{\chi}_1^0$	1-2 μ	-	Yes	15.9	230 GeV	$0.4 < \tau < 2 \text{ ns}$	ATLAS-CONF-2013-058
		CMSB, $\tilde{t}_L \rightarrow \gamma\tilde{g}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	1.0 TeV	$1.5 < \tau < 156 \text{ ms}, \text{BR}(\tilde{g}) > 1, m(\tilde{g}) > 108 \text{ GeV}$	1304.6310
RPV		$\tilde{g}\tilde{g} \rightarrow \text{anti-}t\bar{t} \rightarrow \text{anti-}W^+W^- \tilde{\chi}_1^0$	1 μ , displ. vtx	-	-	20.3	1.0 TeV	ATLAS-CONF-2013-052	
		LFV $pp \rightarrow \tilde{t}_L \tilde{t}_L^* \rightarrow X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 e, μ	-	-	4.6	1.61 TeV	$A_{\tilde{g}\tilde{g}} > 0.10, A_{\tilde{g}\tilde{g}} < 0.05$	1212.1272
		LFV $pp \rightarrow \tilde{t}_L \tilde{t}_L^* \rightarrow e, \tilde{\nu}_\tau \rightarrow e(p) + \tau$	1 $e, \mu + \tau$	-	-	4.6	1.3 TeV	$A_{\tilde{g}\tilde{g}} > 0.10, A_{\tilde{g}\tilde{g}} < 0.05$	1212.1272
		Linear RPV CMSM	1 e, μ	7 jets	Yes	4.7	1.2 TeV	$m(\tilde{g}) > 300 \text{ GeV}, A_{123} > 0$	ATLAS-CONF-2012-140
Other	$\tilde{t}_L\tilde{t}_L \rightarrow t\bar{t}\tilde{\chi}_1^0$	0	-	Yes	20.7	760 GeV	$m(\tilde{g}) > 300 \text{ GeV}, A_{123} > 0$	ATLAS-CONF-2013-036	
	$\tilde{t}_L\tilde{t}_L \rightarrow t\bar{t}\tilde{\chi}_1^0$	3 $e, \mu + \tau$	-	Yes	20.7	350 GeV	$m(\tilde{g}) > 80 \text{ GeV}, A_{123} > 0$	ATLAS-CONF-2013-036	
	$\tilde{t}_L\tilde{t}_L \rightarrow t\bar{t}\tilde{\chi}_1^0$	0	6-7 jets	Yes	20.3	916 GeV	$\text{BR}(\tilde{g}) > 0.01, \text{BR}(\tilde{g}) < 0.01$	ATLAS-CONF-2013-081	
	$\tilde{t}_L\tilde{t}_L \rightarrow t\bar{t}\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 b	Yes	20.7	880 GeV	$\text{BR}(\tilde{g}) > 0.01, \text{BR}(\tilde{g}) < 0.01$	ATLAS-CONF-2013-007	
Other	Scalar gluon pair, $\text{sgluon} \rightarrow q\bar{q}$	0	4 jets	-	4.8	sgluon	incl. limit from 1110.2993	1210.4826	
	Scalar gluon pair, $\text{sgluon} \rightarrow t\bar{t}$	2 e, μ (SS)	1 b	Yes	14.3	800 GeV	ATLAS-CONF-2013-051		
	WIMP interaction (DS, Dirac)	0	mono-jet	Yes	10.5	764 GeV	$m(\tilde{g}) > 80 \text{ GeV}$, limit of 687 GeV for DS	ATLAS-CONF-2012-147	
	$\sqrt{s} = 7 \text{ TeV}$ full data	$\sqrt{s} = 8 \text{ TeV}$ partial data	$\sqrt{s} = 8 \text{ TeV}$ full data				Mass scale [TeV]		
							10^{-1}		
							1		

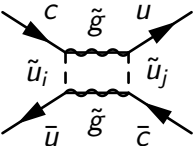
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

One common assumption in SUSY searches

The superpartner spectrum is **flavor-blind**

Flavor Issues

Low-E observables constrain the SUSY flavor structure



A Feynman diagram showing a gluon exchange between two quarks of different flavors, u and c . The incoming quarks are labeled u and c , and the outgoing quarks are labeled $\bar{c}$ and $\bar{u}$. The internal lines are squarks, labeled $\tilde{u}_i$ and $\tilde{u}_j$. The gluon is labeled $\tilde{g}$. The diagram is followed by an implication arrow $\Rightarrow$ pointing to the equation $\delta_{ij} \sim \frac{(\Delta \tilde{m}^2)_{ij} K_{ij}}{\bar{m}^2}$, which is then followed by a double-headed arrow $\Leftrightarrow$ pointing to a list of three bullet points.

$$\delta_{ij} \sim \frac{(\Delta \tilde{m}^2)_{ij} K_{ij}}{\bar{m}^2} \Leftrightarrow$$

- 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 + $\cancel{E}_T$

Rough bounds:

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

Flavor in SUSY searches

But in fact

MFV is over constraining

sfermions can have mass splittings and/or mixing

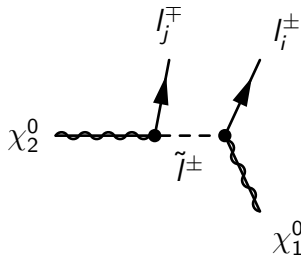
bounds on $\delta_{ij} = \frac{(\Delta\tilde{m}^2)_{ij}}{\tilde{m}^2} K_{ij}$ allow: small mixing $\Leftrightarrow$ large splitting

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



Galon & Shadmi arXiv:1108.2220 [hep-ph]

Di-lepton endpoint

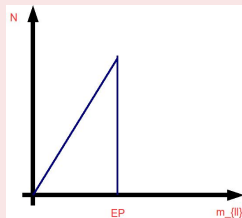
$$m_{ll}^2|_{\text{endpoint}} = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}}^2}$$

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

With Flavor

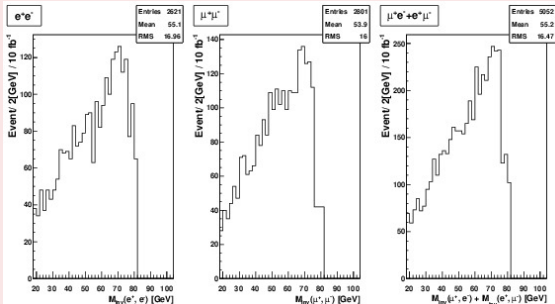
Mixing

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

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 1st 2nd 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

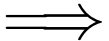
- mixings affect detection (especially for $\tilde{t}, \tilde{b}, \tilde{c}$)

Blanke, Giudice, Paradisi, Perez & Zupan , Agrawal & Frugiuele

Extend: GMSB



Flavored GMSB (FGM)



Gauge Mediated SUSY Breaking (GMSB)

The (minimal) GMSB superpotential

Dine, Nelson & Shirman

Dine, Nelson, Nir & Shirman

$$W = X\phi\bar{\phi} + Y^u QH^u u^c + Y^d QH^d d^c + Y^l LH^d e^c$$

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

Main Features

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

Evolving down with RGEs

Minimally Flavor Violating (MFV) Theory

Coupling to Messengers

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

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

In general

- Messenger can couple to visible fields in various ways

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

- **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

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

Upshot

flavor dependent

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

FGM: Model Symmetries

Shadmi & Szabo

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

• $N_5 \geq 2$ for: y^U and y^D, y^L

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

Soft Terms

At $\mu = M$:

- non-zero A-terms

$$A \sim -\frac{1}{(4\pi)^2} Y y^2 \frac{F}{M}$$

- soft masses $_{2-loop}$:

$$\tilde{m}^2 \sim \frac{1}{(4\pi)^4} (g^4 - g^2 y^2 + y^4 \pm Y^2 y^2) \left| \frac{F}{M} \right|^2$$

- soft masses $_{1-loop}$: (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

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

Messenger flavor structure

$$y_u, y_d, y_l$$

Add a flavor theory

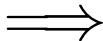
- Explain SM mass hierarchies & mixings within the **flavor theory**

Automatically

- same flavor theory **controls new couplings**

non-degenerate squarks

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



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

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

$\Rightarrow$

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

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

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

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

Assigning messenger charges

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

determines the pattern of

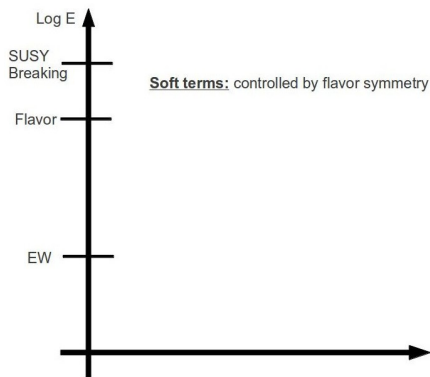
$$y^u \Rightarrow \Delta \tilde{m}_u^2 \supset y^{u\dagger} y^u y^{u\dagger} y^u, \quad y^{u\dagger} Y Y^\dagger y^u, \quad Y^\dagger y^u y^{u\dagger} Y, \quad g^2 y^{u\dagger} y^u, \dots$$

we will choose n, m such that

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

Alignment

Usual Alignment

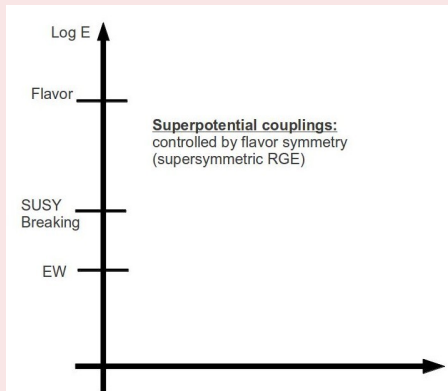


Nir & Seiberg

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

Supersymmetric Alignment

Supersymmetric Alignment



Shadmi & Szabo

- aligned **superpotential couplings**
- can be **low-scale *SUSY***
- soft-terms “inherit” structure
- RGE: **large splittings**

Non-Degenerate Squarks

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

Choose (m, n) such that

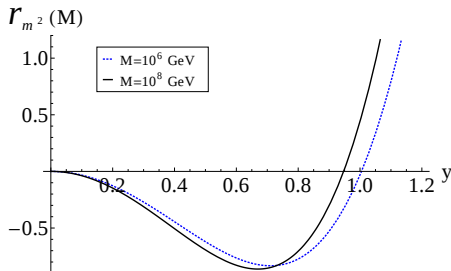
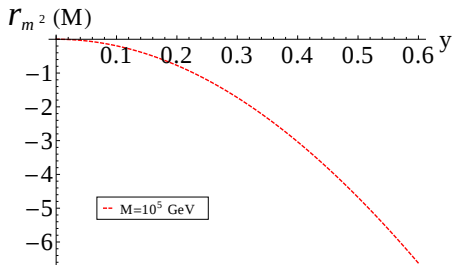
$$(y_u)_{ij} \approx y \delta_{i2} \delta_{j2}$$

$\Rightarrow$

Then

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

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



Phenomenology

Light charm- and strange-squarks

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

Heavy up- and down-squarks

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

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 $M = 500 \text{ TeV}, F/M = 200 \text{ TeV}$

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

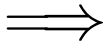
② $M = 400 \text{ TeV}, F/M = 150 \text{ TeV}$

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

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
- ...



MFV-like FGM

so for $m_h \approx 126$ GeV

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

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

$$W = X(\bar{T}_i T_i + \bar{D}_i D_i) + Y^u QH_u u^c + Y^d QH_d d^c + Y^l LH_d e^c + yQ_3 \bar{D} t^c$$

At $\mu = M$:

- non-zero A-terms

$$A \sim -\frac{1}{(4\pi)^2} Y y^2 \frac{F}{M}$$

- soft masses $_{2-loop}$:

$$\tilde{m}^2 \sim \frac{1}{(4\pi)^4} (g^4 - g^2 y^2 + y^4 \pm Y^2 y^2) \left| \frac{F}{M} \right|^2$$

- soft masses $_{1-loop}$: (for $M < 10^7$ GeV)

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

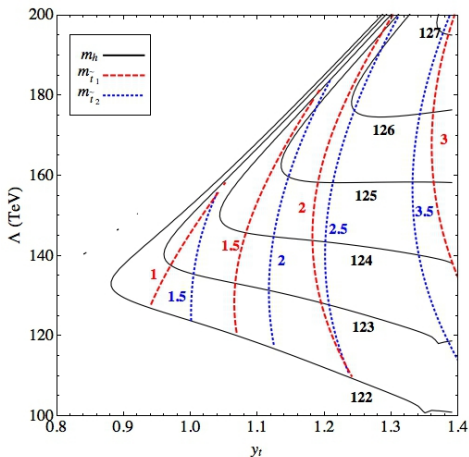
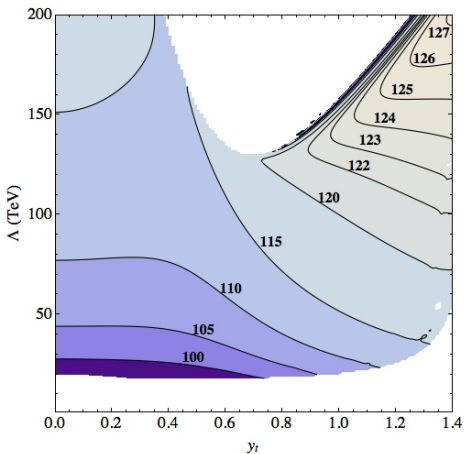
Higgs mass

Two possibilities for Higgs mass

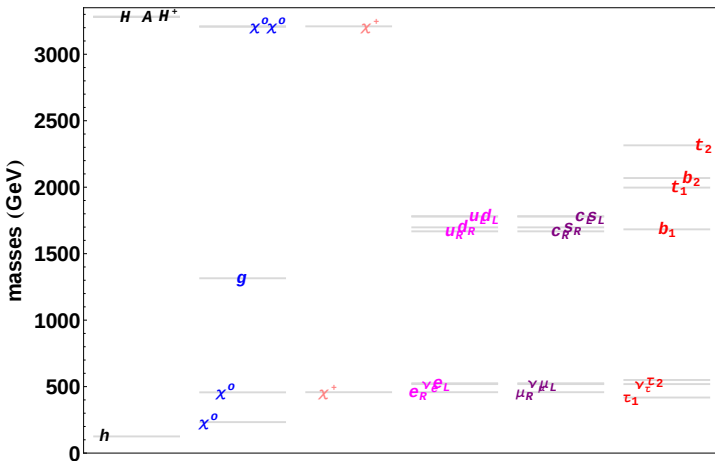
- mostly stop A-terms, LL, RR $\pm$ contributions cancel (1-loop: mainly low scales): light spectra.
- enhanced by the large LL,RR stop masses - heavy stops

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

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



Example Spectrum

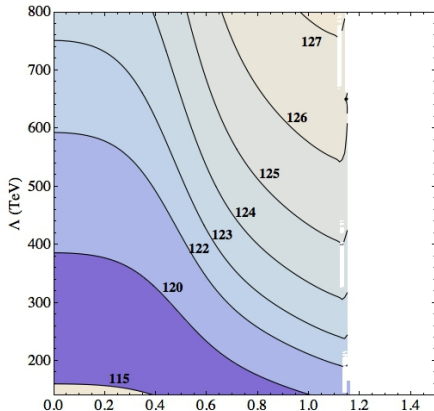


$$\begin{aligned} M &= 400 \text{ TeV} \\ \Lambda &= 165 \text{ TeV} \\ \tan \beta &= 10 \\ y_t &= 1.2 \end{aligned}$$

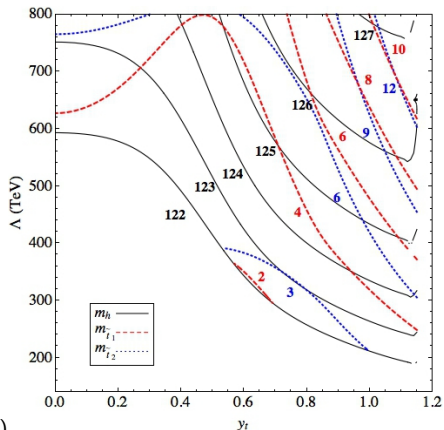
- $m_{\chi^0} = 233 \text{ GeV}$
- $m_{\tilde{q}} \sim 1.7 \text{ TeV}$
- $m_{\tilde{g}} \sim 1.3 \text{ TeV}$
- $m_{\tilde{t}_1} \sim 2 \text{ TeV}$

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

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

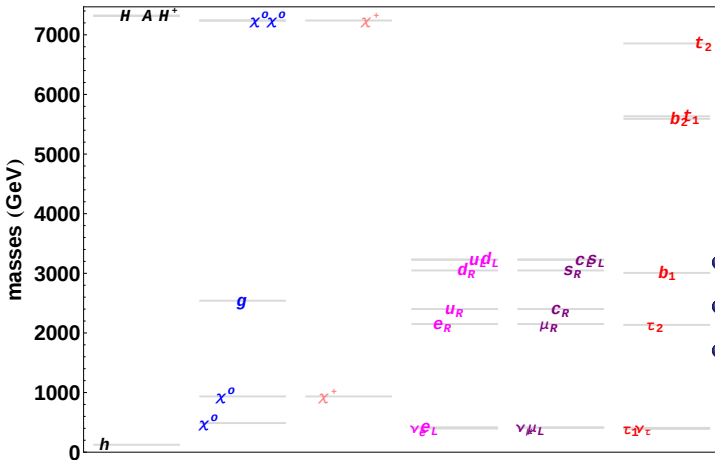


- No tachyonic stops (negative 1-loop is negligible)
- $y_t \gtrsim 1.2 \rightarrow$ tachyonic staus, EWSB problems



- Need Λ large $\Rightarrow$ heavy spectrum

Example Spectrum



$$M = 10^{12} \text{ GeV}$$

$$\Lambda = 355 \text{ TeV}$$

$$\tan \beta = 10$$

$$y_t = 1.14$$

$$m_{\tau_I} = 390 \text{ GeV}$$

$$m_{\tilde{u}_R} = 2401 \text{ GeV}$$

$$m_{\tilde{g}} = 2540 \text{ GeV}$$

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

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

- Soft masses:

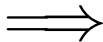
$$(\delta \tilde{m}_{u_R})_{22}, (\delta \tilde{m}_{u_R})_{33}, (\delta \tilde{m}_{Q_L})_{33}$$

- 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



Calculation of Soft Terms

Analytic Continuation into superspace

~~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

$$\int d^4\theta \phi^\dagger Z \phi \quad \Rightarrow \quad m_{\tilde{\phi}}^2 = - \frac{\partial^2 \ln Z}{\partial(\ln X^\dagger) \partial(\ln X)} \frac{F^\dagger F}{M^\dagger M}$$

Giudice & Rattazzi

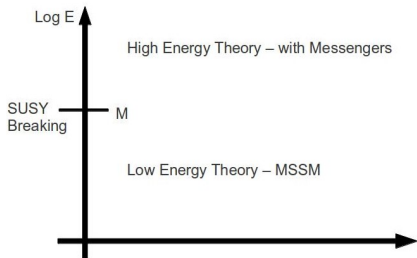
Arkani-Hamed, Giudice, Luty & Rattazzi

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

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

Calculation of Soft Terms

Schematically



Analytic Continuation

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

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

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 $\Rightarrow \tilde{m}^2|_{2-loop}$

Calculation of Soft Terms

Simplified Model - High-E theory

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

Kinetic terms

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

and assume $Z_{ij}(\mu = \Lambda) = \delta_{ij}$

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

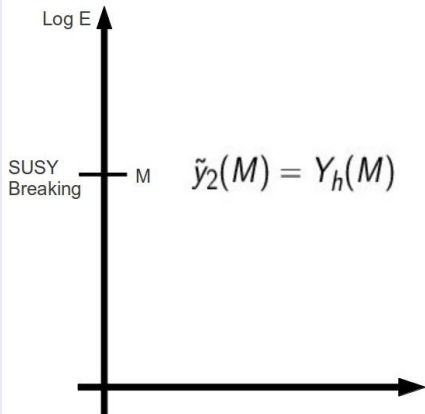
Things to note:

- 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

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

where

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

Bounds On δs

$$(\delta_{ij}^q)_{MM} = \frac{\Delta \tilde{m}_{q_j q_i}^2}{\tilde{m}_q^2} (K_M^q)_{ij} (K_M^q)_{jj}^*,$$

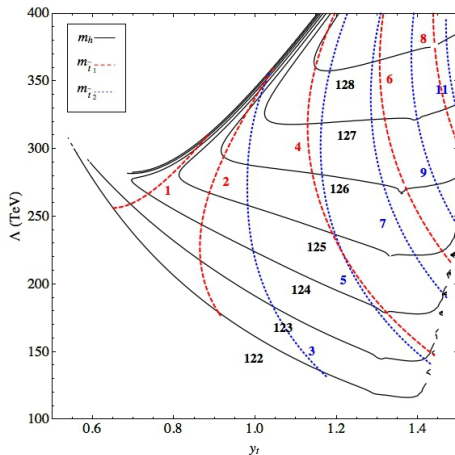
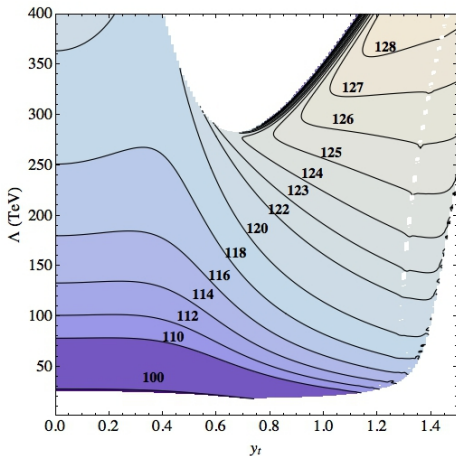
where $\Delta \tilde{m}_{q_j q_i}^2 = m_{q_j}^2 - m_{q_i}^2$, and $\tilde{m}_q^2$

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

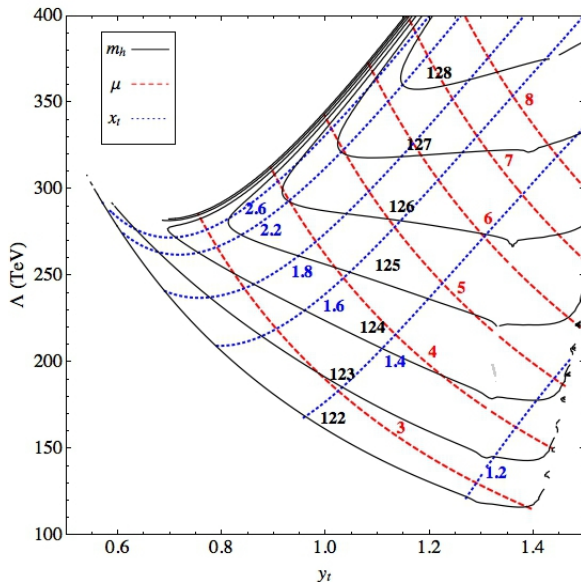
Table: The upper bounds on $(\delta_{ij}^q)_{MM}$, taken from Isidori, Nir & Perez, but assuming order-one phases, for $m_{\tilde{q}} = 1$ TeV and $m_{\tilde{g}}/m_{\tilde{q}} = 1$.

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

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



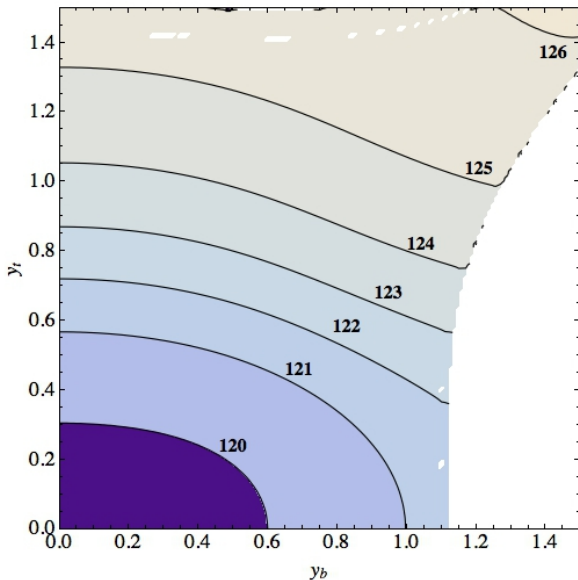
Higgs Mass



$$M = 900 \text{ TeV}, \tan \beta = 10$$

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

Higgs Mass - y_t and y_b



$$\begin{aligned} \Lambda &= 230 \text{ TeV} \\ M &= 10^8 \text{ GeV} \\ \tan \beta &= 10 \end{aligned}$$

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

A-terms 3rd-generation limit

$$\begin{aligned}A_{3,3}^U &= -\frac{Y_t}{16\pi^2} [3y_t^2 + y_b^2] \frac{F}{M} \\A_{3,3}^D &= -\frac{Y_b}{16\pi^2} [3y_b^2 + y_t^2] \frac{F}{M} \\A_{3,3}^L &= -\frac{3Y_\tau y_\tau^2}{16\pi^2} \frac{F}{M}\end{aligned}$$

and also

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

Soft Squared Masses 3rd-generation limit

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

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

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

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

Soft Squared Masses 3rd-generation limit

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

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

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

1-Loop Soft Squared Masses

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

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

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

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

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