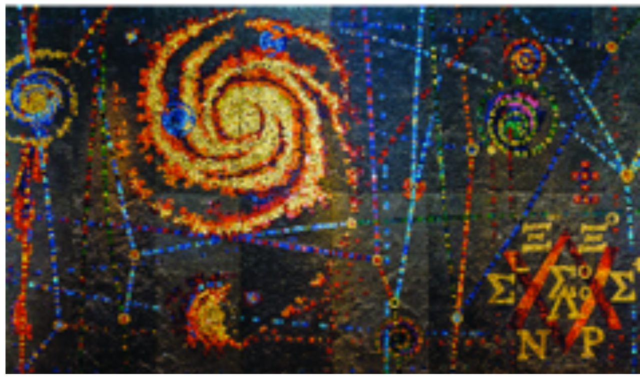
21 - 26 JULY 2014, MANCHESTER, ENGLAND
SUSY2014
THE 22ND INTERNATIONAL CONFERENCE ON SUPERSYMMETRY AND UNIFICATION OF FUNDAMENTAL INTERACTIONS



Natural Supersymmetry Breaking with Meta-stable Vacua

Moritz McGarrie

with

S.Abel (IPPP, Durham)

ArXiv: 1404:1318 (JHEP)

FACULTY OF PHYSICS WARSAW UNIVERSITY

UNIVERSITY OF THE WITWATERSRAND JOHANNESBURG

UNIVERSITAS VARSOVIENSIS

Natural SUSY checklist

- The 126 GeV Higgs- NMSSM
  or non decoupled D-terms
  e.g. (Aoife Bharucha, Andreas Goudelis & MM) 1310.4500

$$m_{h_0}^2 = m_z^2 \cos(2\beta) + \lambda^2 v_{ew}^2 \sin(2\beta)$$

- Light stops (lighter than 1st & 2nd generation squarks)

$$\delta m_{H_u}^2 \sim -\frac{3y_t^2 m_{\tilde{t}}^2}{4\pi^2} \mathrm{Log}\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

- Dynamical explanation? Soft masses cannot be the same

$$m^2_{(Q,U,D)_3} << m^2_{(Q,U,D)_{1,2}}$$

- Connection to Flavour? $Y_u \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_t \end{pmatrix}$, $Y_d \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_b \end{pmatrix}$, $Y_e \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_\tau \end{pmatrix}$

- No (excluded) FCNC's please!

- Realistic models of SUSY breaking? - ISS magnetic SQCD

A common problem!

Other approaches such as making At large, still need to explain why stops are lighter than 1st two generations? e.g. "Large At Without the Desert"-ArXiv: 1405:1038

Why? $$m^2_{(Q,U,D)_3} << m^2_{(Q,U,D)_{1,2}}$$

Typically for all mSUGRA, GMSB, AMSB etc soft masses look like this: $$m^2_{Q,U,D} \sim \Lambda^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

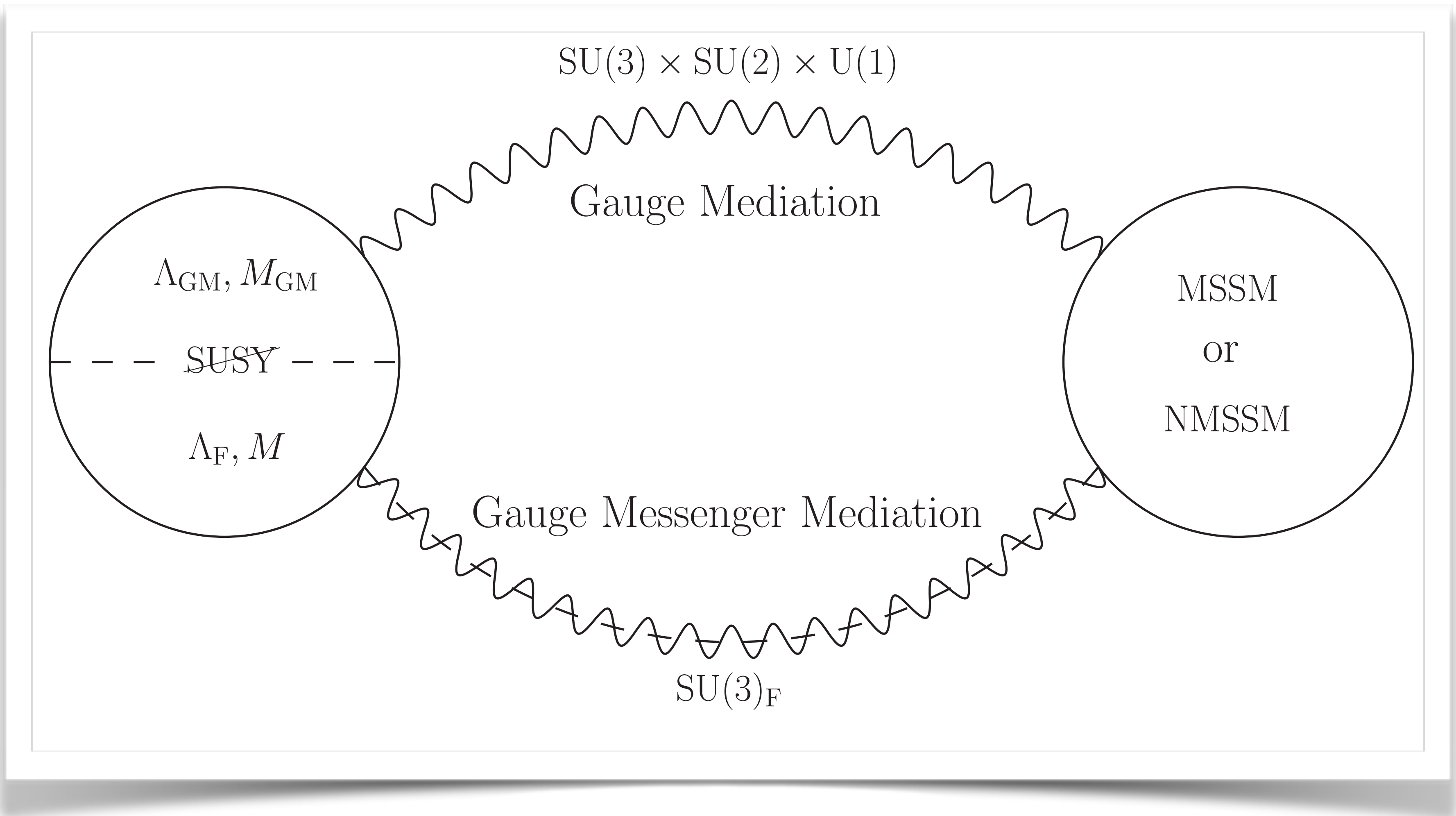
But exclusions look like this:

$$m^2_{Q,U,D} \sim \Lambda^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{matrix} \left.\right\} \rightarrow \text{ ~> 1.5 TeV exclusions} \\ \rightarrow \sim > 400 \text{ GeV exclusions} \end{matrix}$$

First two generations degenerate to reduce FCNC's an SU(2)_F ?

(F.Bruemmer, A.Weiler & MM) 1312.0935
(S.Abel & MM) 1404.1318

Flavour Gauge Messengers



- Extend gauge mediation to include a gauged flavour group
- Explain Yukawas and SUSY breaking
- Fields break SU(3)_F and SUSY at the same time
- Fully dynamical origin in terms of Meta-stable SUSY breaking

How to Gauge flavour?

Field	G_{SM}	$SU(3)_L \times SU(3)_R \to SU(3)_F$
$\hat{Q}^f$	$(\mathbf{2}, \frac{1}{6}, \mathbf{3})$	$(\overline{\mathbf{3}}, 1)$
$\hat{L}^f$	$(\mathbf{2}, -\frac{1}{2}, \mathbf{1})$	$(\overline{\mathbf{3}}, \mathbf{1})$
$\hat{H}_d$	$(\mathbf{2}, -\frac{1}{2}, \mathbf{1})$	$(\mathbf{1},\mathbf{1})$
$\hat{H}_u$	$(\mathbf{2}, \frac{1}{2}, \mathbf{1})$	$(\mathbf{1},\mathbf{1})$
$\hat{D}^f$	$(\mathbf{1}, \frac{1}{3}, \overline{\mathbf{3}})$	$(\mathbf{1},\mathbf{3})$
$\hat{U}^f$	$(\mathbf{1}, -\frac{2}{3}, \overline{\mathbf{3}})$	$(\mathbf{1},\mathbf{3})$
$\hat{E}^f$	$(\mathbf{1}, 1, \mathbf{1})$	$(\mathbf{1}, \mathbf{3})$
$\hat{\nu}^f$	$(\mathbf{0}, 1, \mathbf{1})$	$(\mathbf{1}, \mathbf{3})$

Gauge this flavour group

Include right handed neutrinos

$SU(3)_F$ is anomaly free and $G_{SM} \times SU(3)_F$ mixed anomalies vanish!

We can gauge it…

…. but we still need to Higgs SU(3)_F

(S.Abel & MM) 1404.1318

Gauge messengers=

Recipe:

- Gauge a group
- Higgs a group
- Fields that Higgs that group also break SUSY

Flavour?

Non Abelian Froggat-Nielson mechanism

SUSY breaking fields are Flavons!?

From GMSB

$$m^2_{Q,U,D,\mathrm{GMSB}} \sim +\sum_i \frac{g^4_{SM,i}}{(16\pi^2)^2}\left(\frac{F}{M}\right)^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

From flavour gauge mess.

$$\delta m^2_{Q,U,D} = -\frac{g_F^2}{16\pi^2}\left(\frac{F}{M}\right)^2 \begin{pmatrix} \frac{7}{6} & 0 & 0 \\ 0 & \frac{7}{6} & 0 \\ 0 & 0 & \frac{8}{3} \end{pmatrix}$$

Nett

$$m^2_{Q,U,D} \sim \Lambda^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -\# \end{pmatrix}$$

a tachyonic soft term for stops

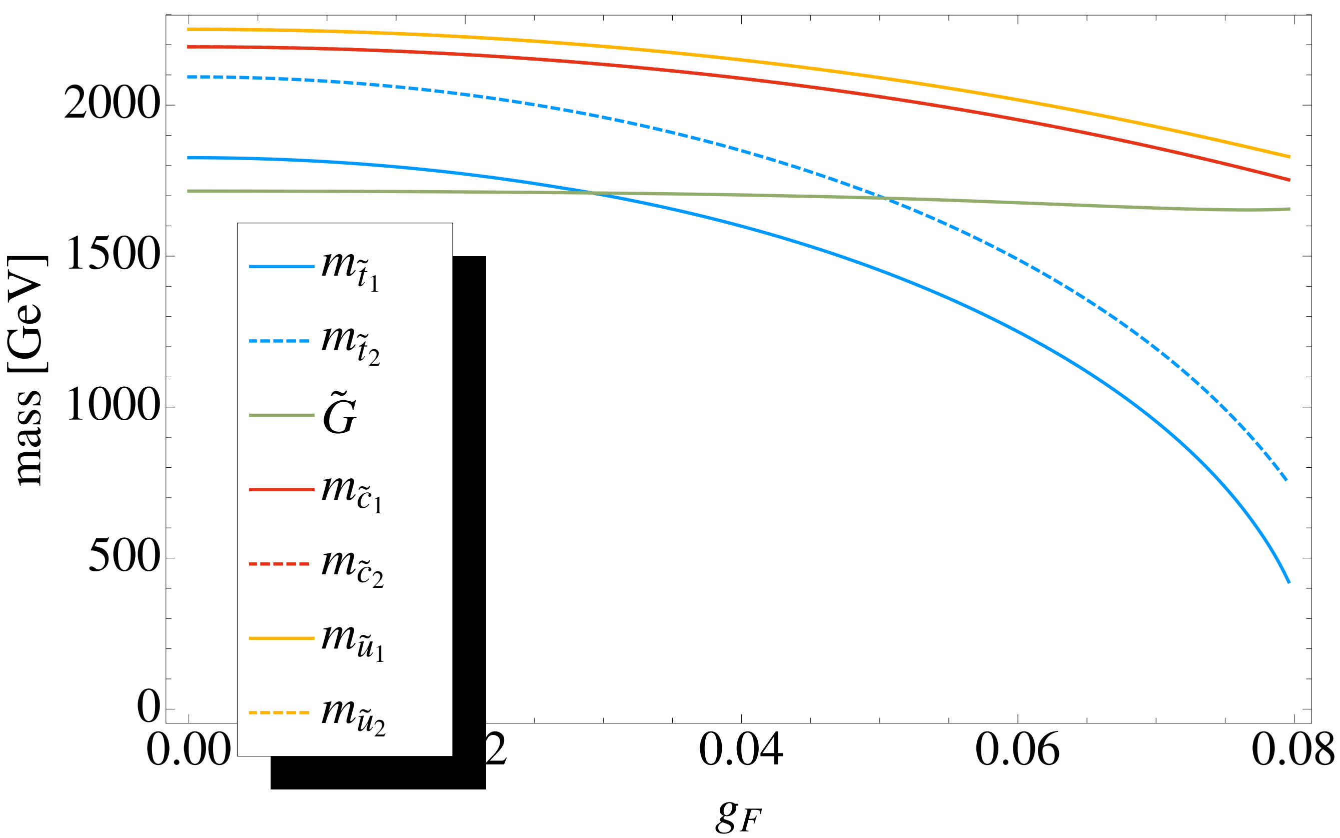
From GMSB

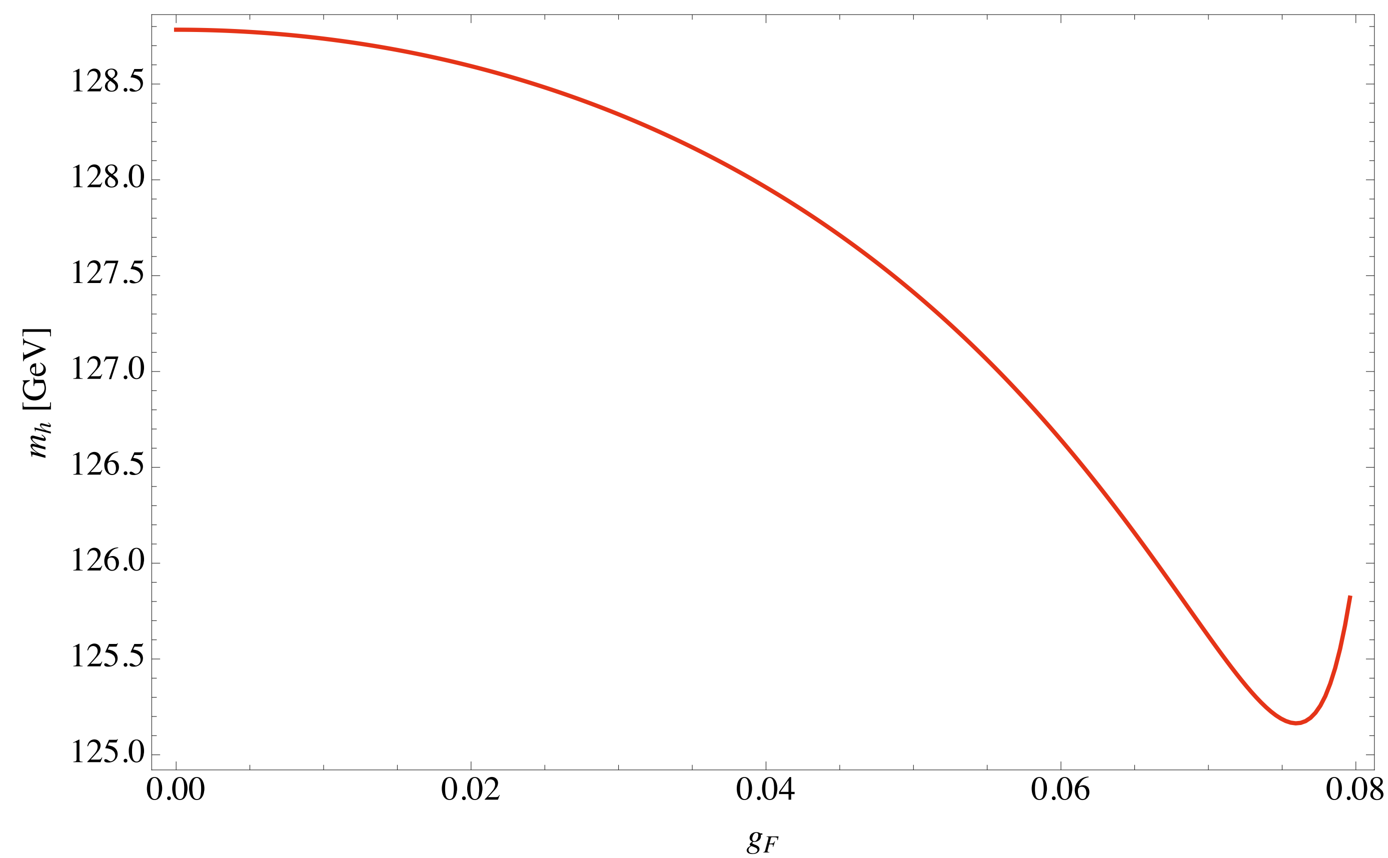
$$m^2_{Q,U,D,\mathrm{GMSB}} \sim + \sum_i \frac{g^4_{SM,i}}{(16\pi^2)^2}\left(\frac{F}{M}\right)^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

From flavour gauge mess.

$$\delta m^2_{Q,U,D} = -\frac{g_F^2}{16\pi^2}\left(\frac{F}{M}\right)^2 \begin{pmatrix} \frac{7}{6} & 0 & 0 \\ 0 & \frac{7}{6} & 0 \\ 0 & 0 & \frac{8}{3} \end{pmatrix}$$

Stick the model into an NMSSM spectrum generator (SPheno)





Squarks and Gluino

Higgs

Figure 2. A plot [Left] of the squark and gluino masses for model 1 with the NMSSM. [Right] a plot of Higgs mass versus g_F for the same range. $\lambda = 0.8$, $\kappa = 0.8$, $v_s = 1000$, $m^2_{H_d} = m^2_{H_u} = 10^5$, $\Lambda = \Lambda_F = 2.3 \times 10^5$, $M = 10^7$, $\tan\beta = 1.5$.

It turns out that this model can embed into magnetic SQCD too!

Field	$SU(\tilde{N})_{\rm mag}$	$SU(3)_L \times SU(3)_R \to SU(3)_F$
Φ	1	$(\mathbf{3}, \overline{\mathbf{3}})$
φ	$\square$	$(\overline{\mathbf{3}}, 1)$
$\tilde{\varphi}$	$\overline{\square}$	$(\mathbf{1},\mathbf{3})$

$$W_{\rm mag} = h {\rm Tr} \varphi \Phi \tilde{\varphi} - \mu^2 {\rm Tr} \Phi .$$

The usual rank condition breaks $SU(3)_F \to SU(2)_F$

$$\mu_{ij} = \begin{pmatrix} \mu & 0 & 0 \\ 0 & \mu & 0 \\ 0 & 0 & \mu \end{pmatrix} \quad \text{and} \quad \varphi^T = \tilde{\varphi} = \begin{pmatrix} \mu \\ \mu \\ 0 \end{pmatrix} \qquad F_\Phi = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & h\mu^2 \end{pmatrix} \quad \text{such that} \quad V_{\rm min} = |h^2 \mu^4| .$$

"Dynamical metastable flavour gauge mediation"

$$\delta m^2_{Q,U,D} = - \frac{g_F^2}{16\pi^2} |h^2 \mu^2| \begin{pmatrix} \frac{8}{9} & 0 & 0 \\ 0 & \frac{8}{9} & 0 \\ 0 & 0 & \frac{20}{9} \end{pmatrix} + \dots$$

Perhaps we can explain Yukawas too!

Couple these fields together

Field	G_{SM}	$SU(3)_L \times SU(3)_R \to SU(3)_F$
$\hat{Q}^f$	$(\mathbf{2}, \frac{1}{6}, \mathbf{3})$	$(\overline{\mathbf{3}}, 1)$
$\hat{L}^f$	$(\mathbf{2}, -\frac{1}{2}, \mathbf{1})$	$(\overline{\mathbf{3}}, \mathbf{1})$
$\hat{H}_d$	$(\mathbf{2}, -\frac{1}{2}, \mathbf{1})$	$(\mathbf{1},\mathbf{1})$
$\hat{H}_u$	$(\mathbf{2}, \frac{1}{2}, \mathbf{1})$	$(\mathbf{1},\mathbf{1})$
$\hat{D}^f$	$(\mathbf{1}, \frac{1}{3}, \overline{\mathbf{3}})$	$(\mathbf{1},\mathbf{3})$
$\hat{U}^f$	$(\mathbf{1}, -\frac{2}{3}, \overline{\mathbf{3}})$	$(\mathbf{1},\mathbf{3})$
$\hat{E}^f$	$(\mathbf{1}, 1, \mathbf{1})$	$(\mathbf{1}, \mathbf{3})$
$\hat{\nu}^f$	$(\mathbf{0}, 1, \mathbf{1})$	$(\mathbf{1}, \mathbf{3})$

Field	$SU(\tilde{N})_{\text{mag}}$	$SU(3)_L \times SU(3)_R \to SU(3)_F$
Φ	1	$(\mathbf{3}, \overline{\mathbf{3}})$
φ	$\square$	$(\overline{\mathbf{3}}, 1)$
$\tilde{\varphi}$	$\overline{\square}$	$(\mathbf{1},\mathbf{3})$

leads to…
$$W = \frac{\lambda_u}{\Lambda} H_u Q \Phi U + \frac{\lambda_d}{\Lambda} H_d Q \Phi D$$

$$\Phi = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \langle X \rangle \end{pmatrix} \quad \text{leads to} \quad Y_u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & Y_t \end{pmatrix}$$

(S.Abel & MM) 1404.1318

Model 2

Field	G_{SM}	$SU(3)_L \times SU(3)_R \to SU(3)_F$
$\hat{Q}^f$	$(\mathbf{2}, \frac{1}{6}, \mathbf{3})$	$(\overline{\mathbf{3}}, 1)$
$\hat{L}^f$	$(\mathbf{2}, -\frac{1}{2}, \mathbf{1})$	$(\overline{\mathbf{3}}, \mathbf{1})$
$\hat{H}_d$	$(\mathbf{2}, -\frac{1}{2}, \mathbf{1})$	$(\mathbf{1},\mathbf{1})$
$\hat{H}_u$	$(\mathbf{2}, \frac{1}{2}, \mathbf{1})$	$(\mathbf{1},\mathbf{1})$
$\hat{D}^f$	$(\mathbf{1}, \frac{1}{3}, \overline{\mathbf{3}})$	$(\mathbf{1},\mathbf{3})$
$\hat{U}^f$	$(\mathbf{1}, -\frac{2}{3}, \overline{\mathbf{3}})$	$(\mathbf{1},\mathbf{3})$
$\hat{E}^f$	$(\mathbf{1}, 1, \mathbf{1})$	$(\mathbf{1}, \mathbf{3})$
$\hat{\nu}^f$	$(\mathbf{0}, 1, \mathbf{1})$	$(\mathbf{1}, \mathbf{3})$

Rank 2

Field	$SU(\tilde{N})_{\mathrm{mag}}$	$SU(3)_L \times SU(3)_R \to SU(3)_F$
Φ	1	$(\mathbf{3}, \overline{\mathbf{3}})$
φ	$\square$	$(\overline{\mathbf{3}}, 1)$
$\tilde{\varphi}$	$\overline{\square}$	$(\mathbf{1},\mathbf{3})$

Rank 1

Field	$SU(\tilde{N})_{\mathrm{mag}}$	$SU(3)_L \times SU(3)_R \to SU(3)_F$
M	1	$(\mathbf{3}, \overline{\mathbf{3}})$
ϕ	$\square$	$(\overline{\mathbf{3}}, 1)$
$\tilde{\phi}$	$\overline{\square}$	$(\mathbf{1},\mathbf{3})$

$$\varphi^T = \tilde{\varphi} = \begin{pmatrix} 0 \\ \mu \\ \mu \end{pmatrix} \quad \text{and} \quad \phi^T = \tilde{\phi} = \begin{pmatrix} 0 \\ 0 \\ \nu \end{pmatrix}$$

$$\frac{\phi}{\Lambda} \sim O(1) \quad \frac{\varphi}{\Lambda} \sim \epsilon \quad \text{leads to} \quad Y_u \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon & \epsilon \\ 0 & \epsilon & 1 \end{pmatrix}$$

Non-Abelian Froggat-Nielson

Many more model building avenues to explore further…

(S.Abel & MM) 1404.1318

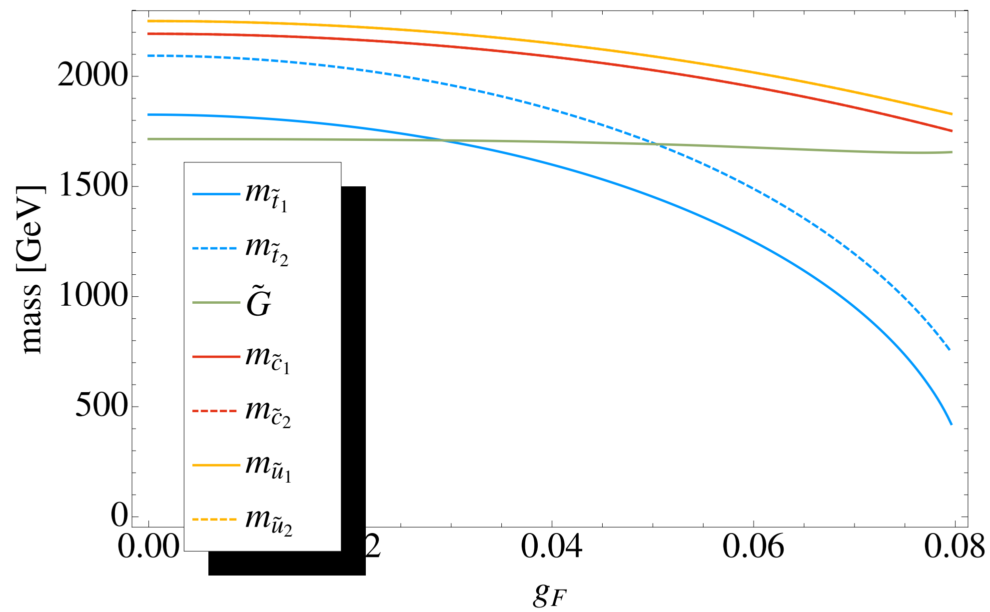
Extensions include: Brane realisations, Holographic realisations, Kutasov duality

Flavour changing neutral currents

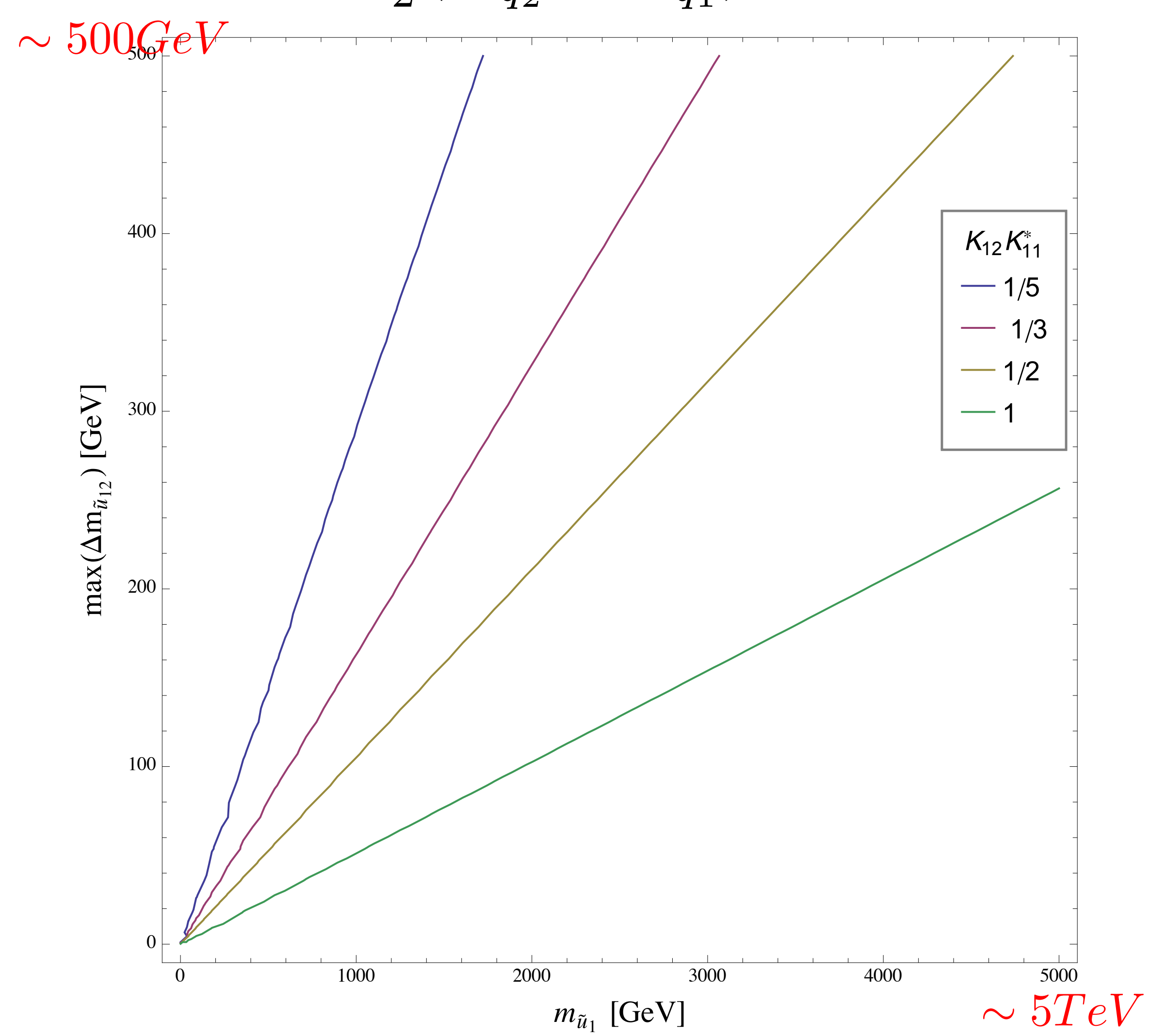
(S.Abel & MM) 1404.1318

$$\delta_{u,12} < 0.1$$

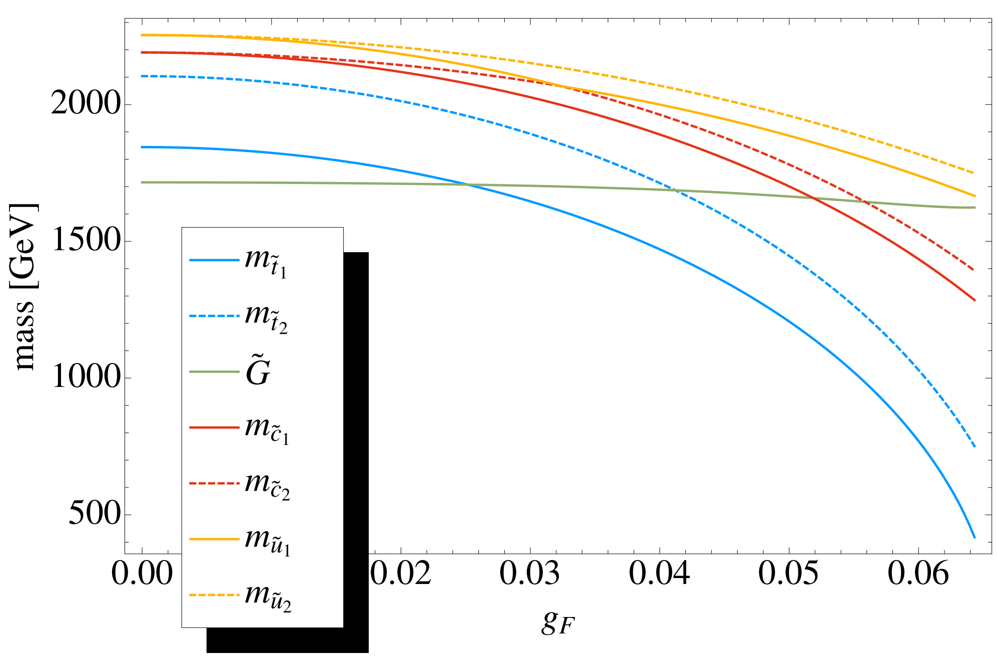
Model 1: degenerate 1st & 2nd



$$\delta_{ij} = \frac{m_{q_2}^2 - m_{q_1}^2}{\frac{1}{2}(m_{q_2}^2 + m_{q_1}^2)} K_{ij} K_{ii}^*$$



Model 2: split 1st & 2nd



Sizeable splittings allowed for multi-TeV 1st and 2nd Gen.

If extended to leptons, we expect Stau NLSP (Gravitino LSP)

Tachyons are natural?!

For a natural cancellation these should be of the same order

$$m_z^2 = -2(m_{H_u}^2 + |\mu|^2) + \ldots$$

Massless stops at Mplanck, turn tachyonic at messenger scale, are turned positive by gluino

stops run positive → $\delta m_{\tilde{t}}^2 = -\frac{8\alpha_s M_3^2}{3\pi} \mathrm{Log}\left(\frac{\Lambda}{M_3}\right)$

$$\delta m_{H_u}^2 \sim -\frac{3y_t^2 m_{\tilde{t}}^2}{4\pi^2} \mathrm{Log}\left(\frac{\Lambda}{m_{\tilde{t}}}\right) \qquad (+) + (-) \sim 0$$

↑

Reduces fine tuning on the Higgs.

Moritz McGarrie

or is it?!

Additional slides

"Large At Without the Desert"

A.Abdalgabar, A.Cornell, A.Deandrea, MM 1405:1038

$$\mathbf{a_u} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_t \end{pmatrix}, \quad \mathbf{a_d} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_b \end{pmatrix}, \quad \mathbf{a_e} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_\tau \end{pmatrix},$$

UV — In many models At= 0 in UV

↓ At runs negative

IR — typically ends up negative a few 100 GeV

Not sufficient to the get correct Higgs mass….

Question: Can we accelerate its running?

1.The Higgs mass 126 GeV

The MSSM at one-loop

top mass

average stop mass

$$m_h^2 \simeq m_z^2 \cos^2(2\beta) + \frac{3}{(4\pi)^2}\frac{m_t^4}{v_{ew}^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

$$126^2 = 91^2 + 81^2$$

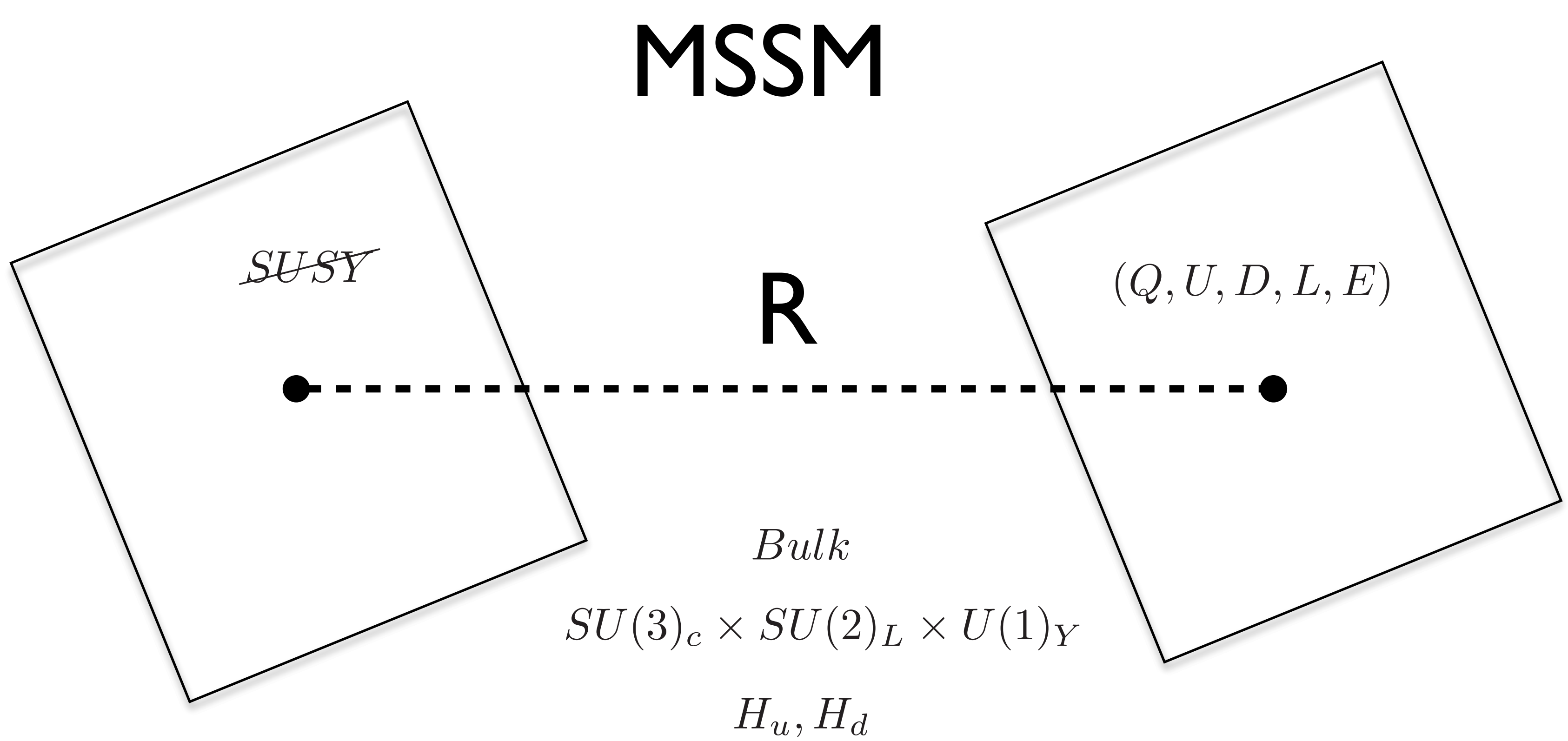
$$X_t = A_t - \mu \cot\beta$$

stop mixing

- Radiative corrections are same order as tree level piece
- corrections run logarithmically in SUSY
- MSSM case implies either heavy stops or large X_t=A_t +…
- Needs 1-2 TeV At or stops to get Higgs mass correct

In 5D you can get large At!

"Power law running"



An extra dimension of radius R.
Additional Kaluza Klein modes enter RGEs @ Q> 1/R

Large At: Independent of the details of SUSY breaking

Split families: Locate different generations in brane or bulk
aesthetically Natural!

$$m^2_{(Q,U,D)_3} << m^2_{(Q,U,D)_{1,2}}$$

Power law running

$$\alpha^{-1}(Q) = \alpha^{-1}(m_z) - \frac{b}{2\pi}\log\frac{Q}{m_z} + \frac{\tilde{b}}{2\pi}\log\frac{Q}{m_{KK}} - \frac{\tilde{b}}{2\pi}(\frac{Q^d}{m_{KK}} - 1)c_d$$

(T.Taylor, G.Veneziano) Phys. Lett. B212 (1988)
(K.Dienes, E.Dudas T. Gherghetta) 9803466
(K.Dienes, E.Dudas, T. Gherghetta) 9806292

"The finite power-law corrections to the Yukawa couplings have the right sign and magnitude to cancel the tree-level terms. This can help to explain the hierarchical structure of the fermion Yukawa couplings."

(A.Abdalagbar, A.Cornell, A.Deandrea, MM) 1405:1038

"Perhaps we can use this to accelerate the evolution of At?"

4+d dimensional MSSM

✓ Always unify
✓ No proton decay
✓ Explains flavour
✓ Large At

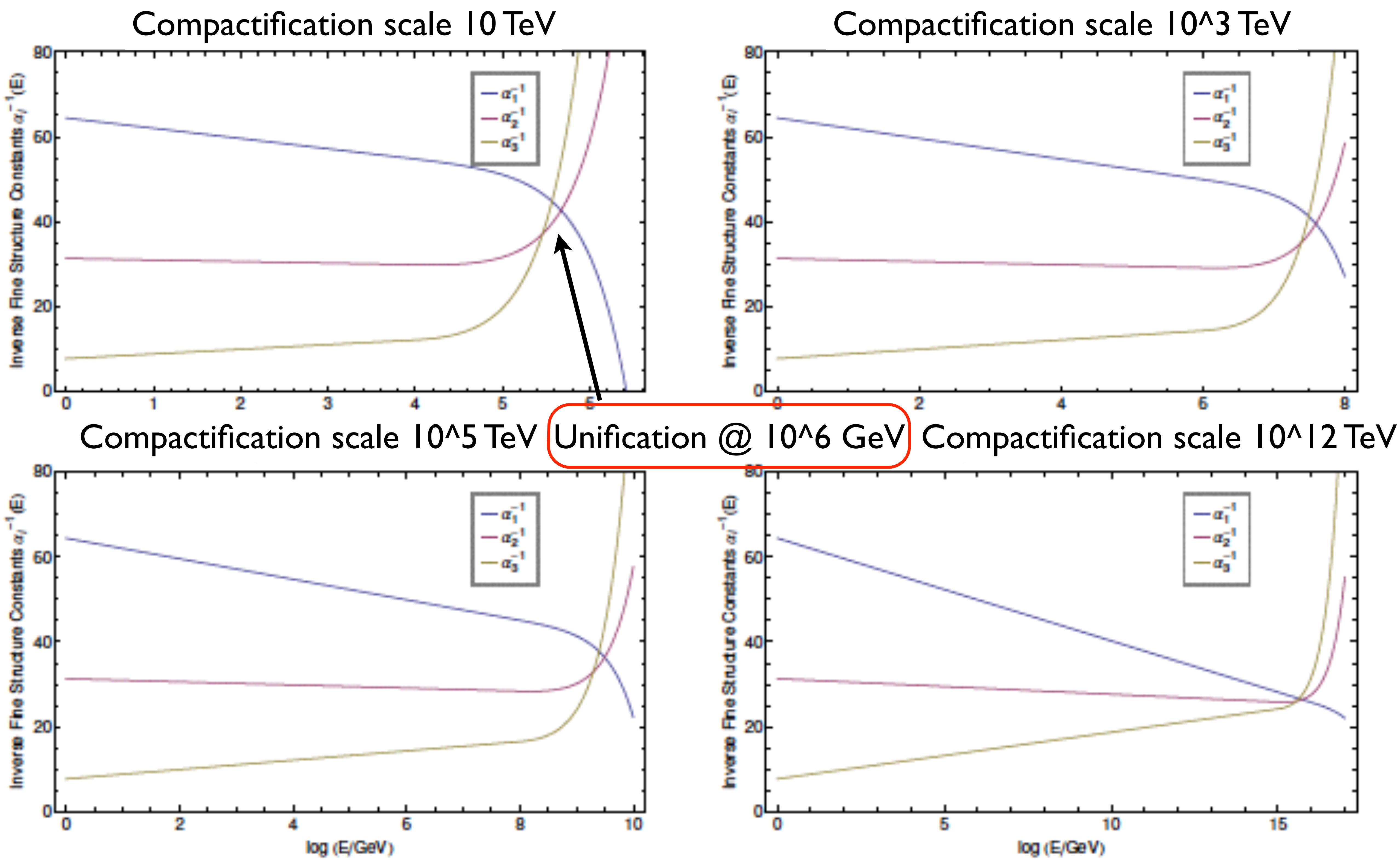


Figure 1. *Running of the inverse fine structure constants $\alpha^{-1}(E)$, for three different values of the compactification scales 10 TeV (top left panel), 10^3 TeV (top right), 10^5 TeV (bottom left) and 10^{12} TeV (bottom right), with M_3 of 1.7 TeV, as a function of log(E/GeV).*

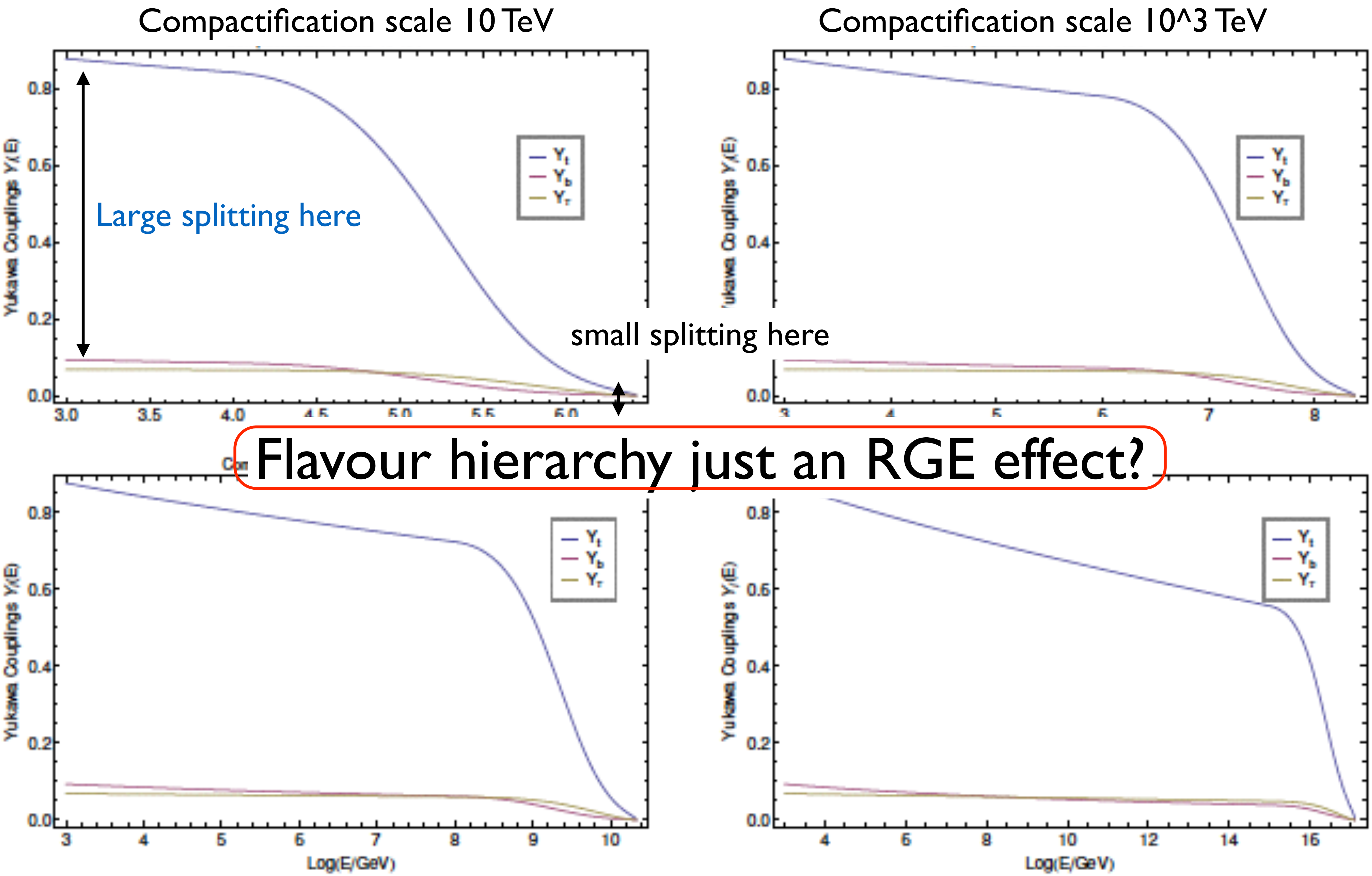


Figure 2. *Running of Yukawa couplings Y_i, for three different values of the compactification scales: 10 TeV (top left panel), 10^3 TeV (top right), 10^5 TeV (bottom left) and 10^{12} TeV (bottom right), with $M_3[10^3]$ of 1.7 TeV, as a function of log(E/GeV).*

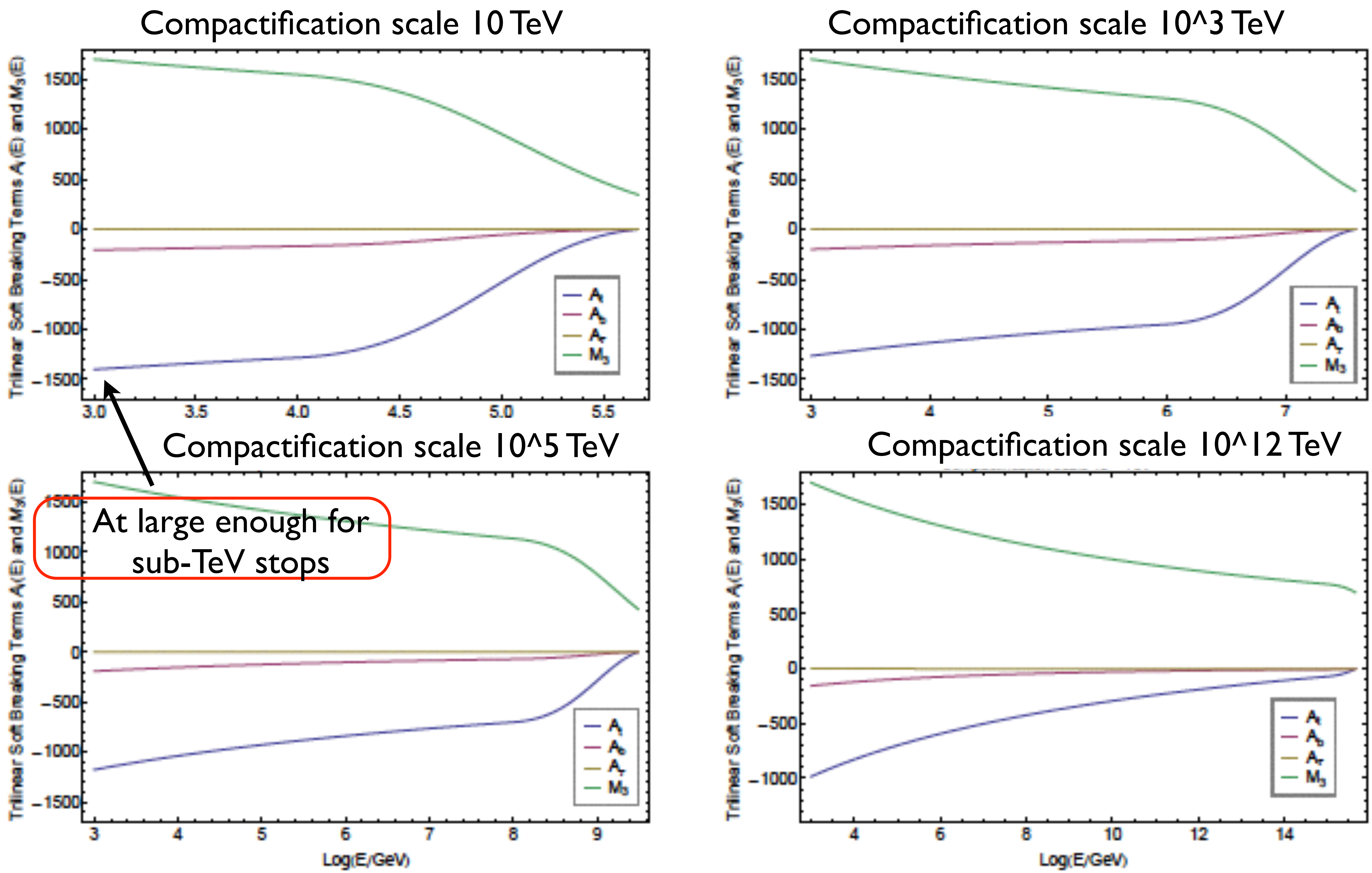
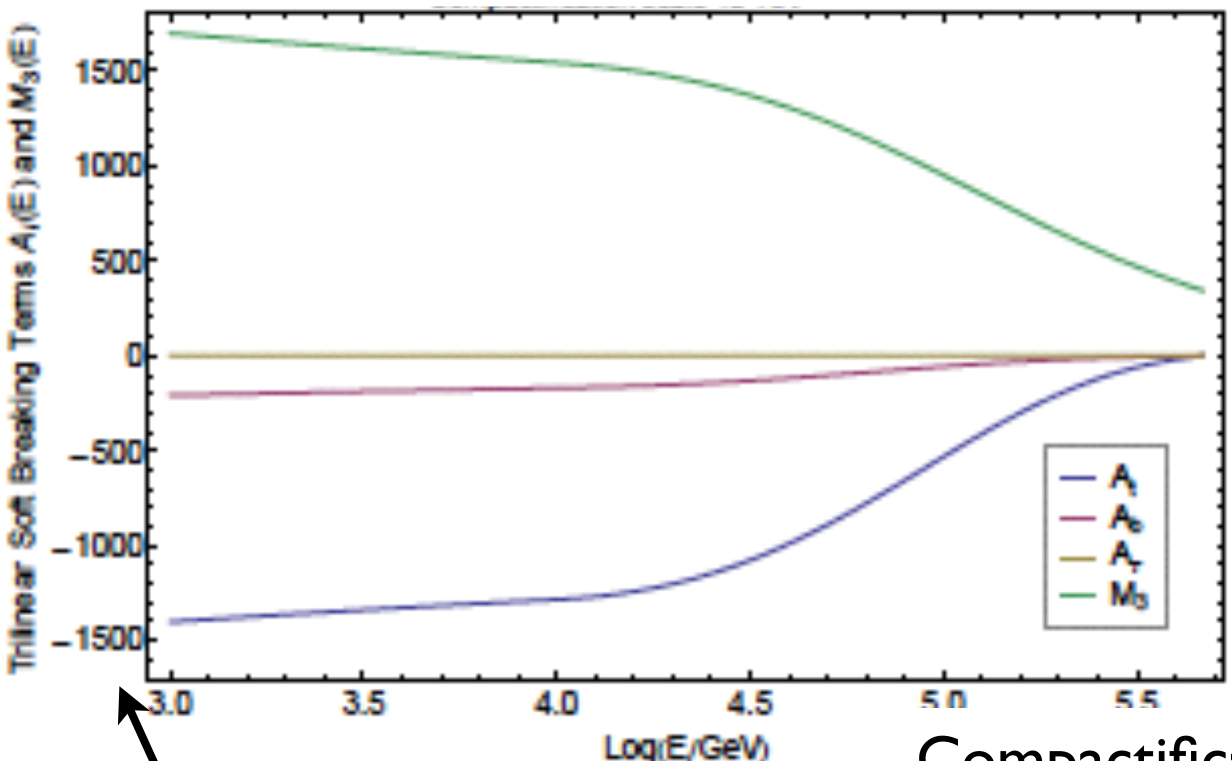
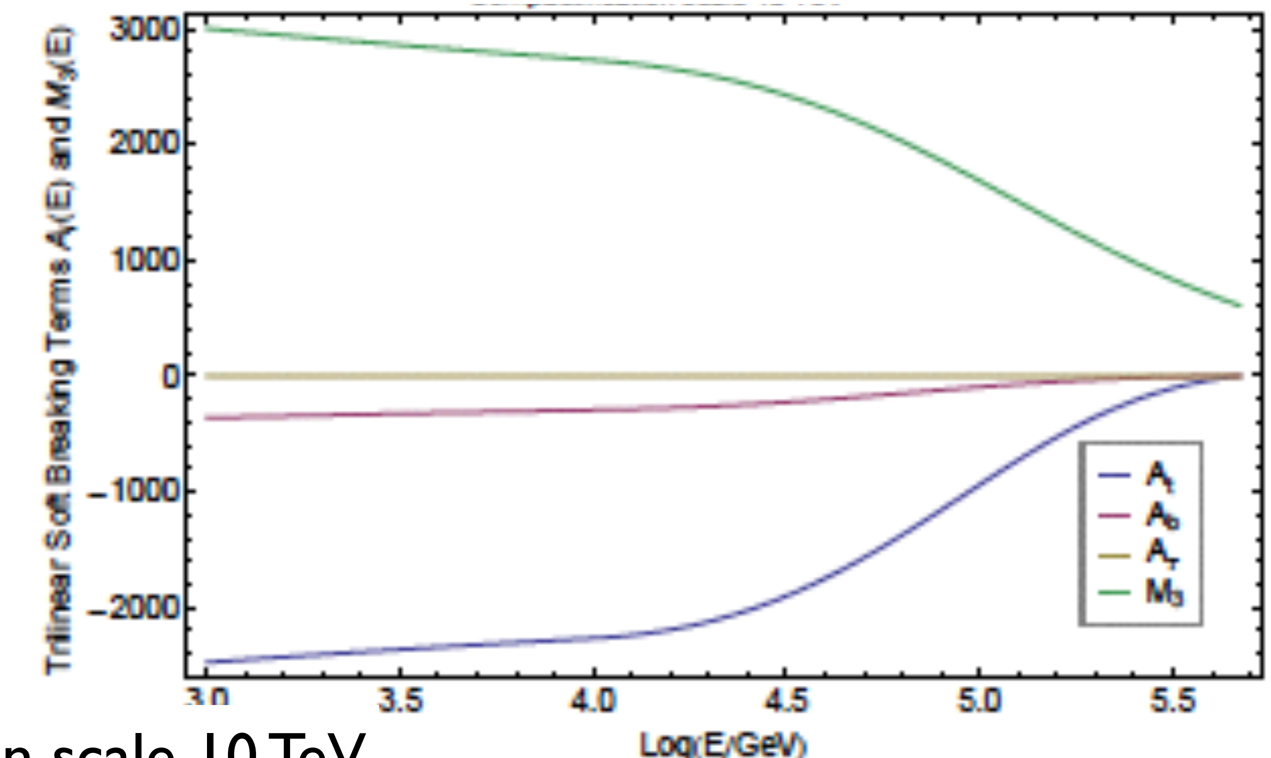


Figure 3. *Running of trilinear soft terms $A_i(3,3)(E)$, for three different values of the compactification scales 10 TeV (top left panel), 10^3 TeV (top right), 10^5 TeV (bottom left) and 10^{12} TeV (bottom right), with $M_3[10^3]$ of 1.7 TeV, as a function of log(E/GeV).*

Compactification scale 10 TeV

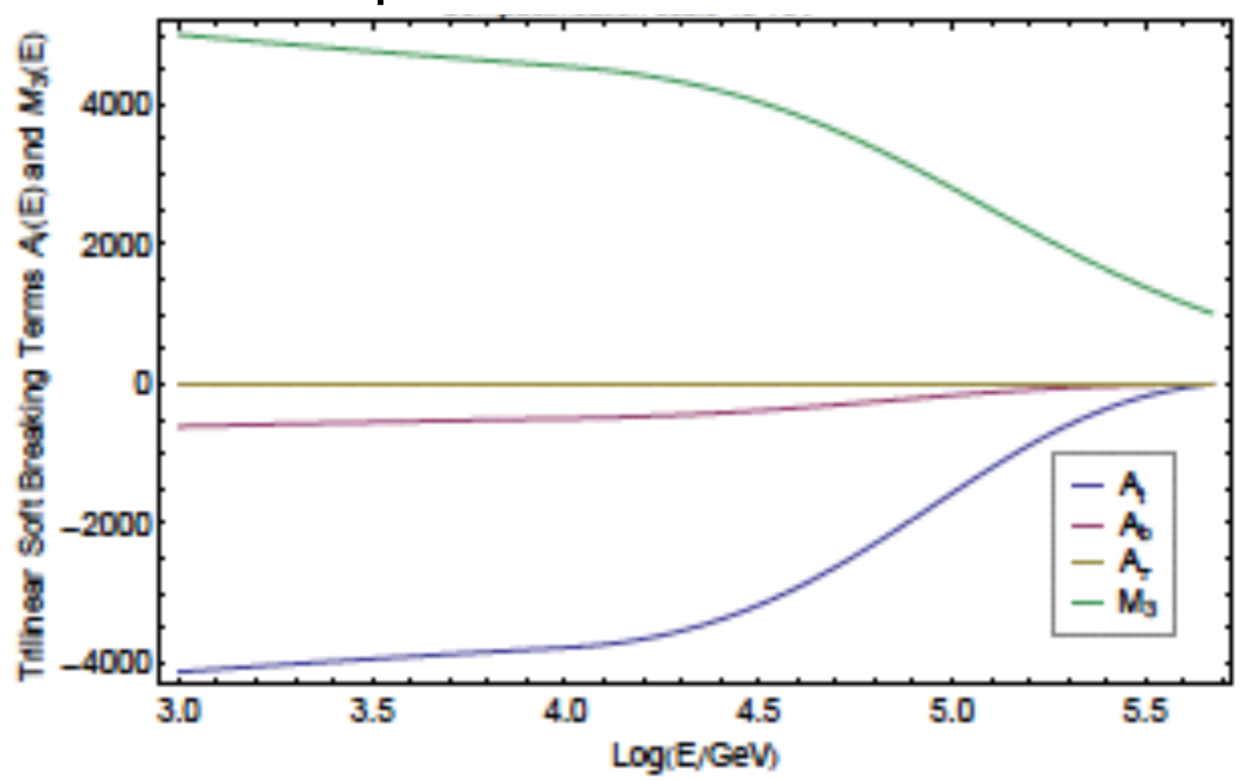


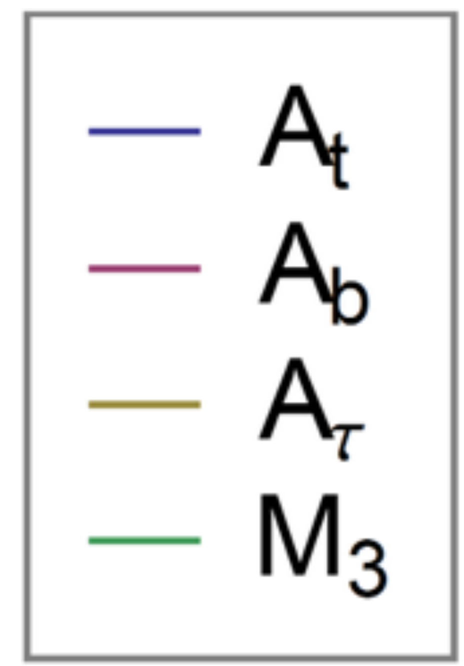
Compactification scale 10 TeV



At large enough for sub-TeV stops

Compactification scale 10 TeV





Larger gluino gives larger At

Moritz McGarrie

Thanks for listening!

Conclusions

- Traditional models are in bad shape
- Perhaps it is time to panic?
- Natural SUSY is motivated from bottom up
- These can have exciting top-down motivations too
- It does mean sacrificing minimality!