Natural SUSY with Dynamical Flavour and Meta-stable Vacua

Moritz McGarrie
with Steve Abel

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

Natural SUSY checklist

- The 126 GeV Higgs- NMSSM (or D-terms) $\longrightarrow$ $m_{h_0}^2 = m_z^2 \cos(2\beta) + \lambda^2 v_{ew}^2 \sin(2\beta)$

- 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

$$m^2_{Q,U,D} \sim \Lambda^2 \left(\begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{array} \right) \begin{array}{l} \} \rightarrow \text{~> 1.5 TeV exclusions} \\ \rightarrow \quad \sim > 400 \text{ GeV exclusions} \end{array}$$

first two generations degenerate to reduce FCNC's

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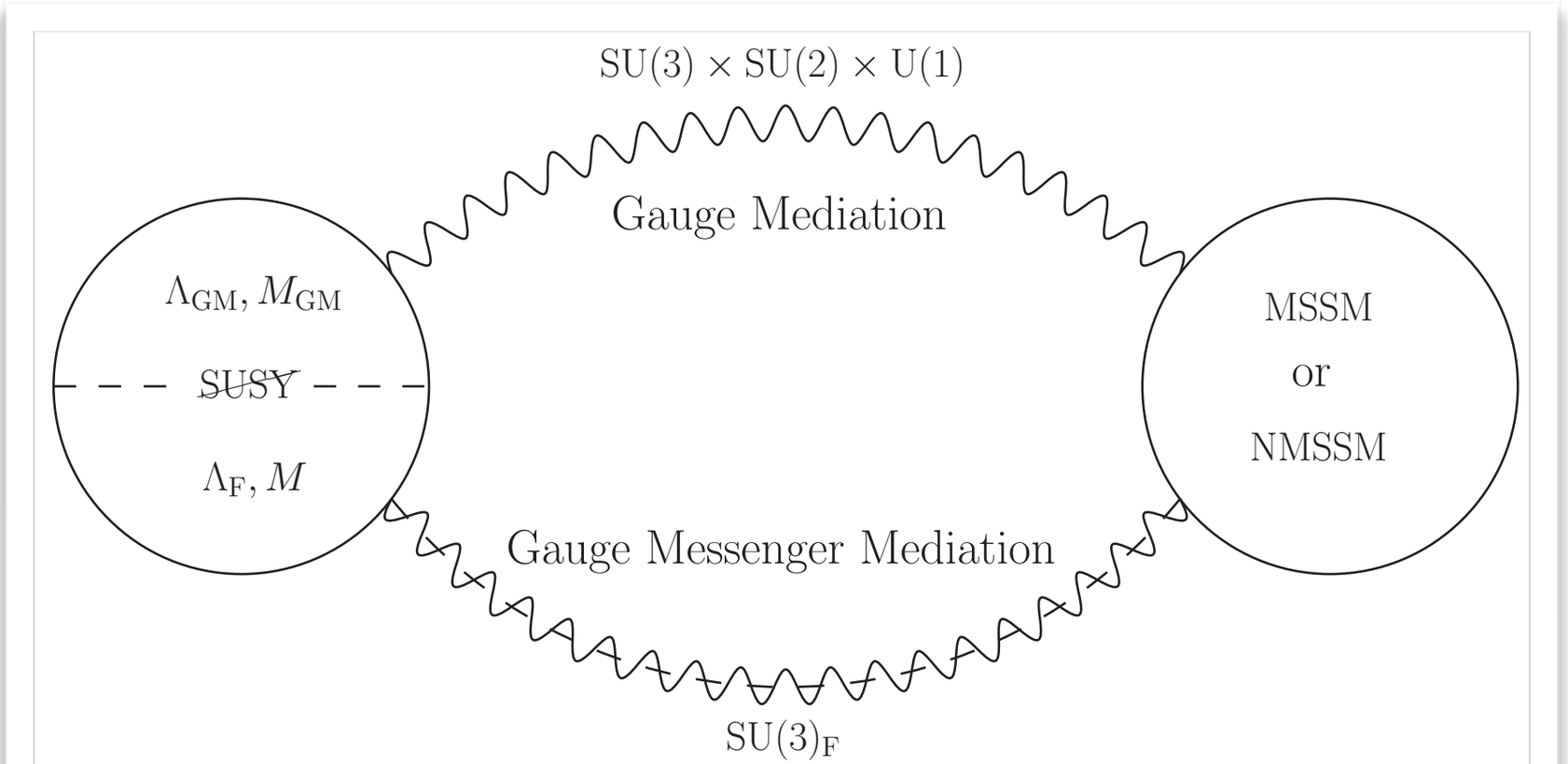
Flavour Gauge Messengers



- 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

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

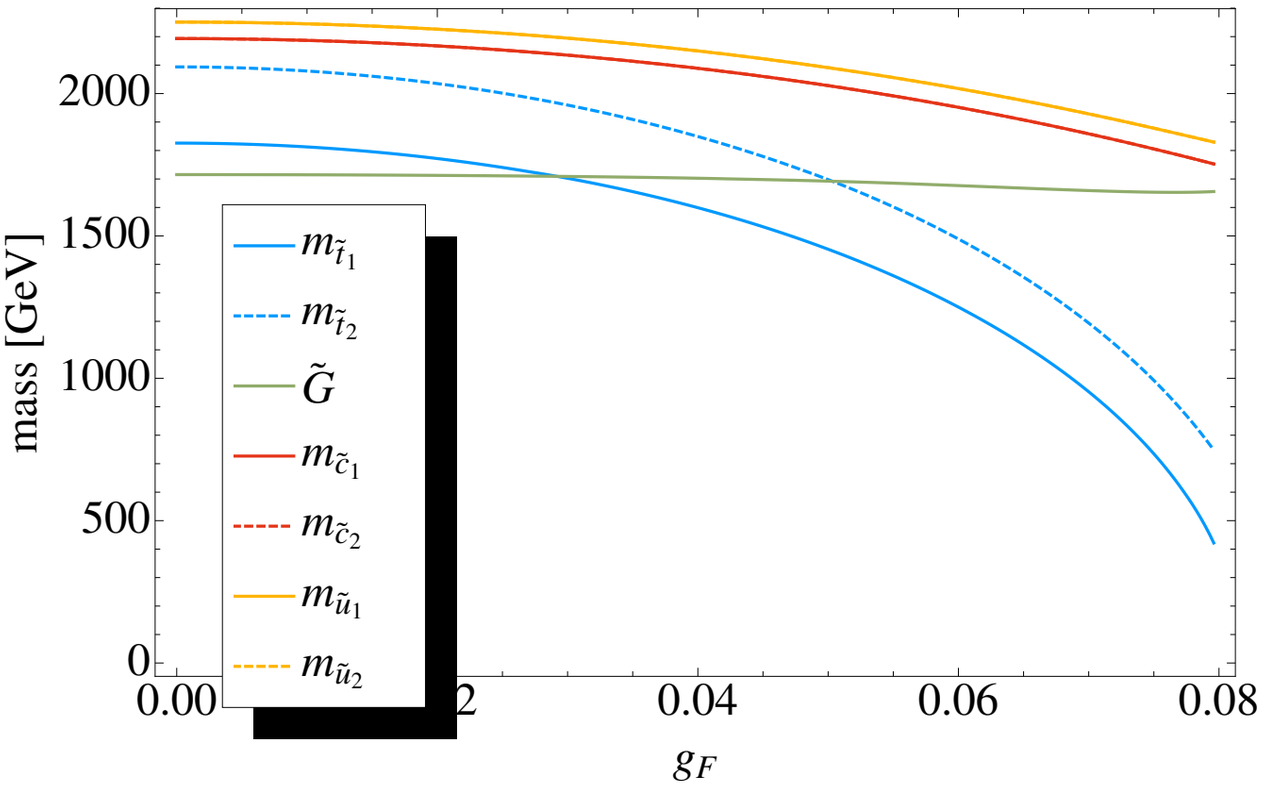
From GMSB

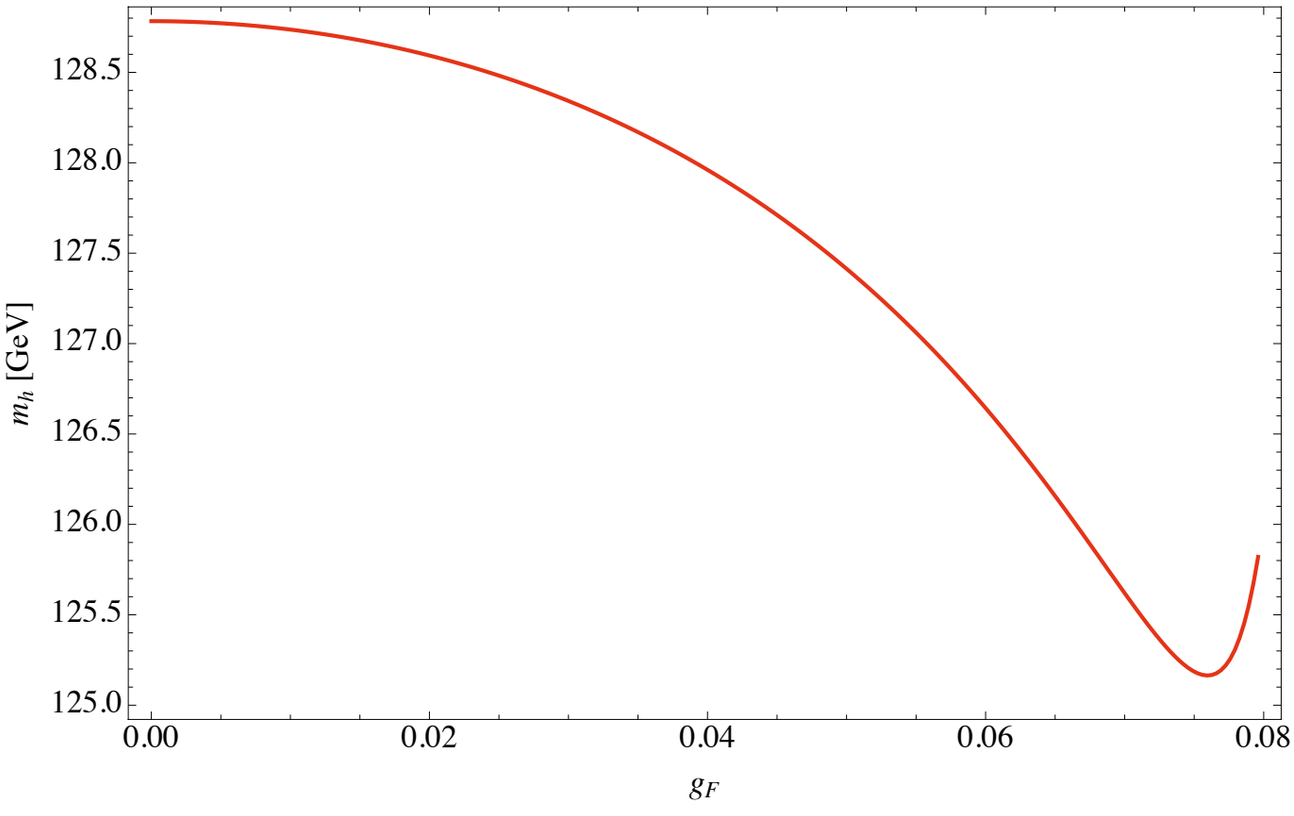
$$m^2_{Q,U,D,\mathrm{GMSB}} \sim + \sum_i \frac{g^4_{SM,i}}{(16\pi^2)^2} \left(\frac{F}{M}\right)^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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. $\lambda = 0.8$, $\kappa = 0.8$, $v_s = 1000$, $m^2_{H_d} = m^2_{H_u} = 10^5$, $\Lambda = \Lambda_F = 2.3 \times 10^5$, $M = 10^7$, $\tan\beta = 1.5$.

Flavour changing neutral currents

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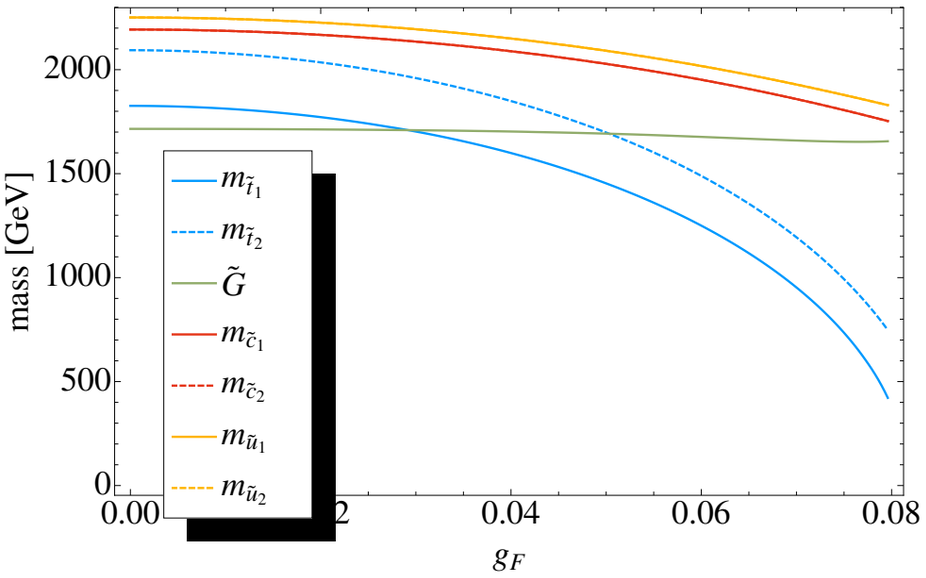
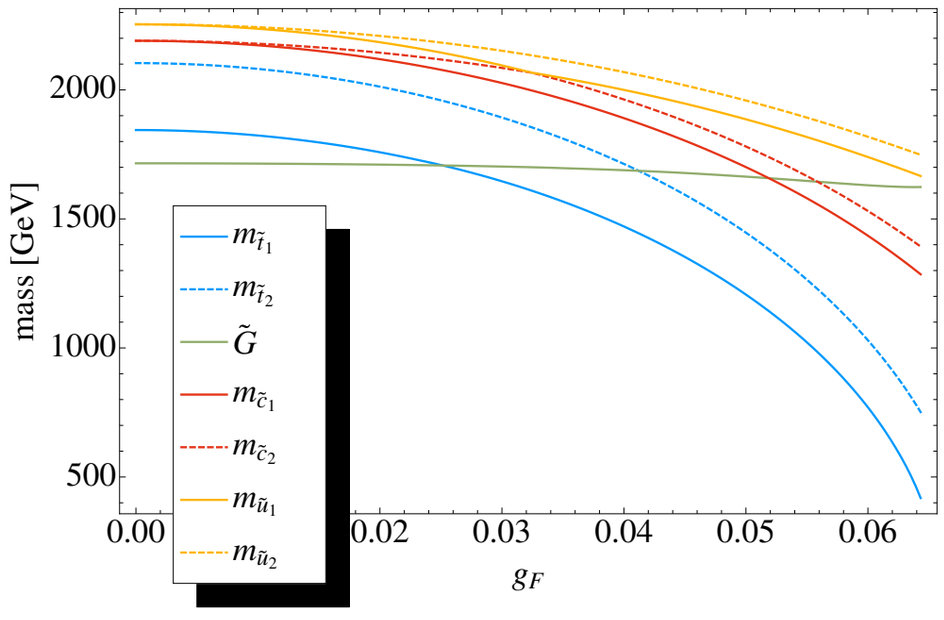
$$\delta_{u,12} < 0.1$$

Model 1: degenerate 1st & 2nd



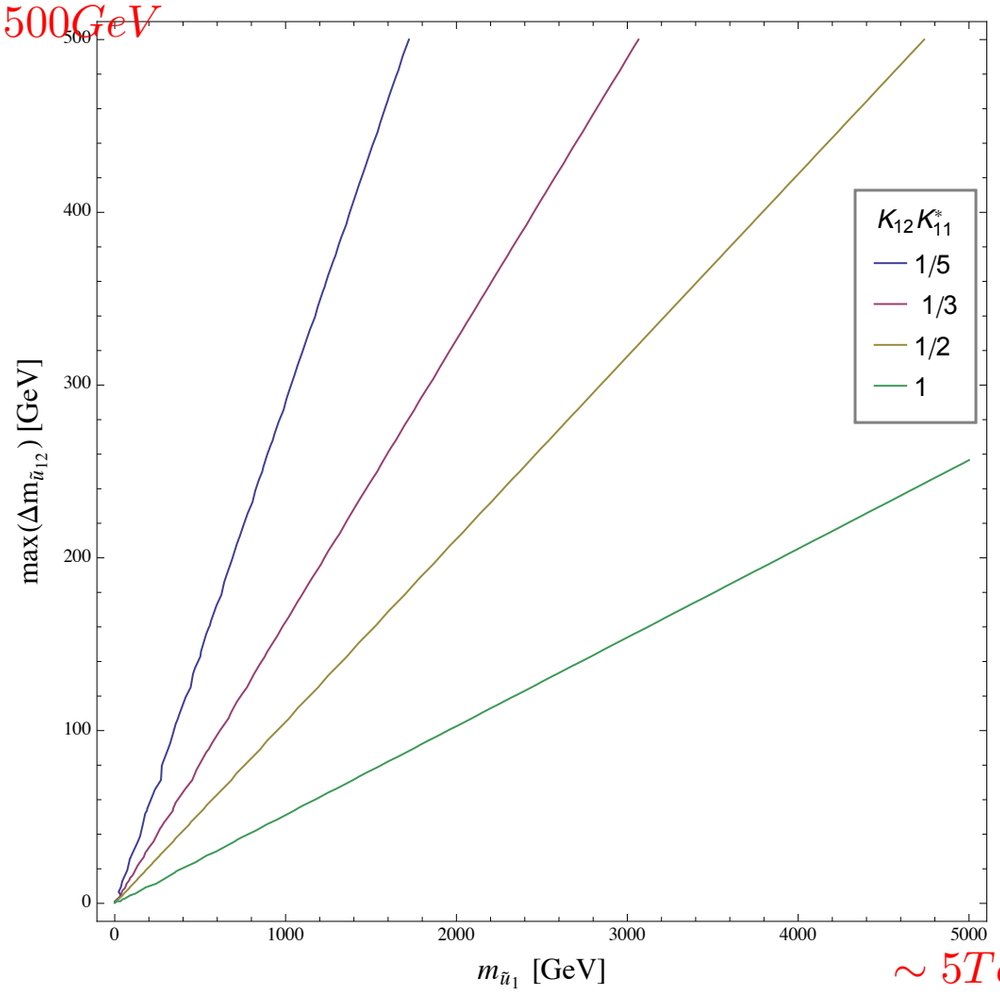
Model 2: split 1st & 2nd



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

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

$\sim 500 GeV$



$\sim 5TeV$

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

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.

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

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

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

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

Many model building avenues to explore further… (S.Abel & MM) 1404.1318

Moritz McGarrie

Thanks for listening!

Model 2

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

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	$\square$	$(\overline{\mathbf{3}}, 1)$
$\tilde{\varphi}$	$\overline{\square}$	$(\mathbf{1},\mathbf{3})$

Rank 2

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

Rank 1

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

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

Non-Abelian Froggat-Nielson

Many more model building avenues to explore further…

(S.Abel & MM) 1404.1318

"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

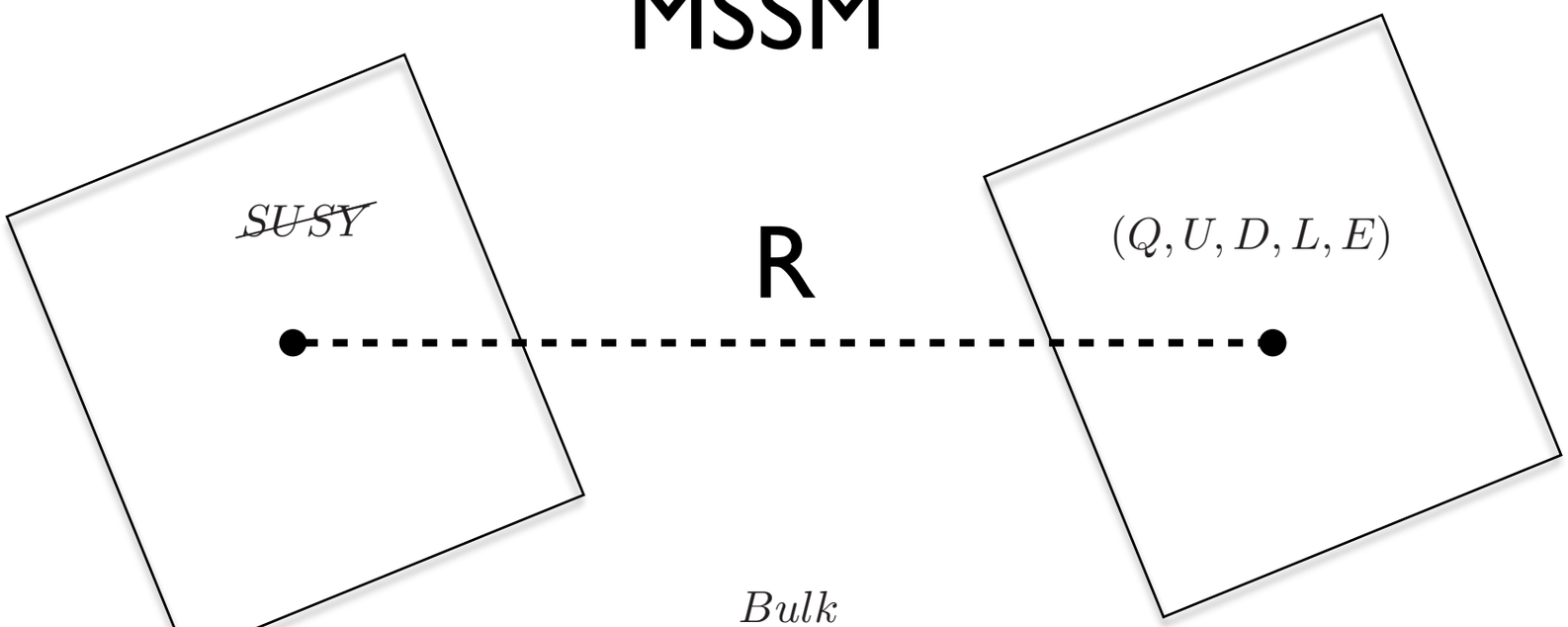
At runs negative

IR typically ends up negative a few 100 GeV

Not sufficient to the get correct Higgs mass….

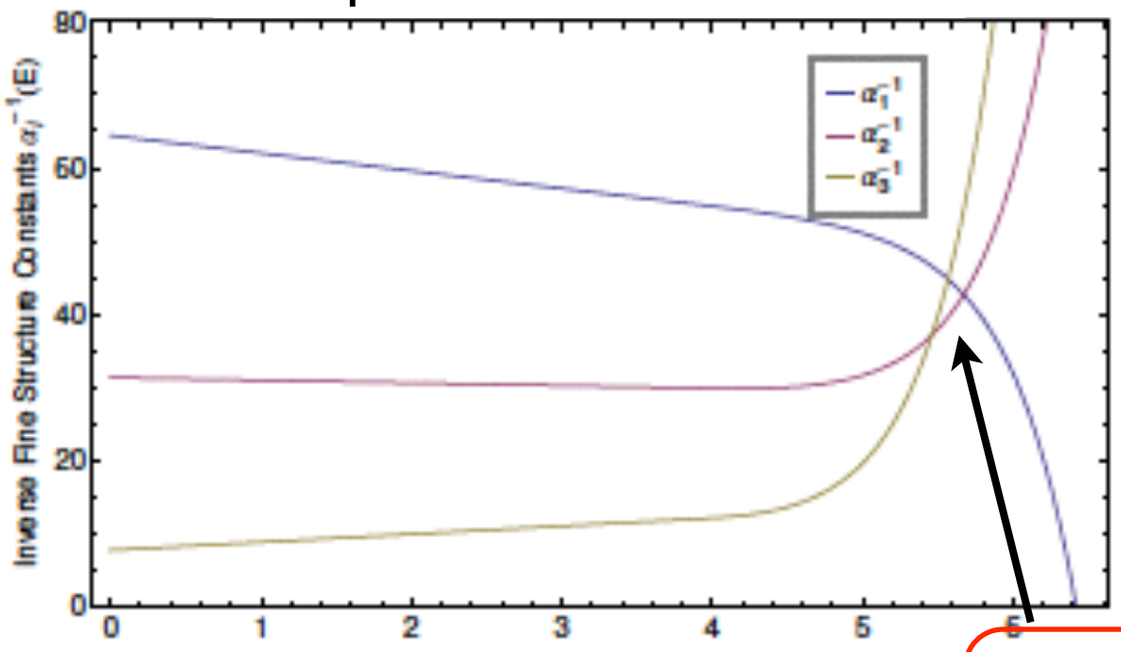
Question: Can we accelerate its running?

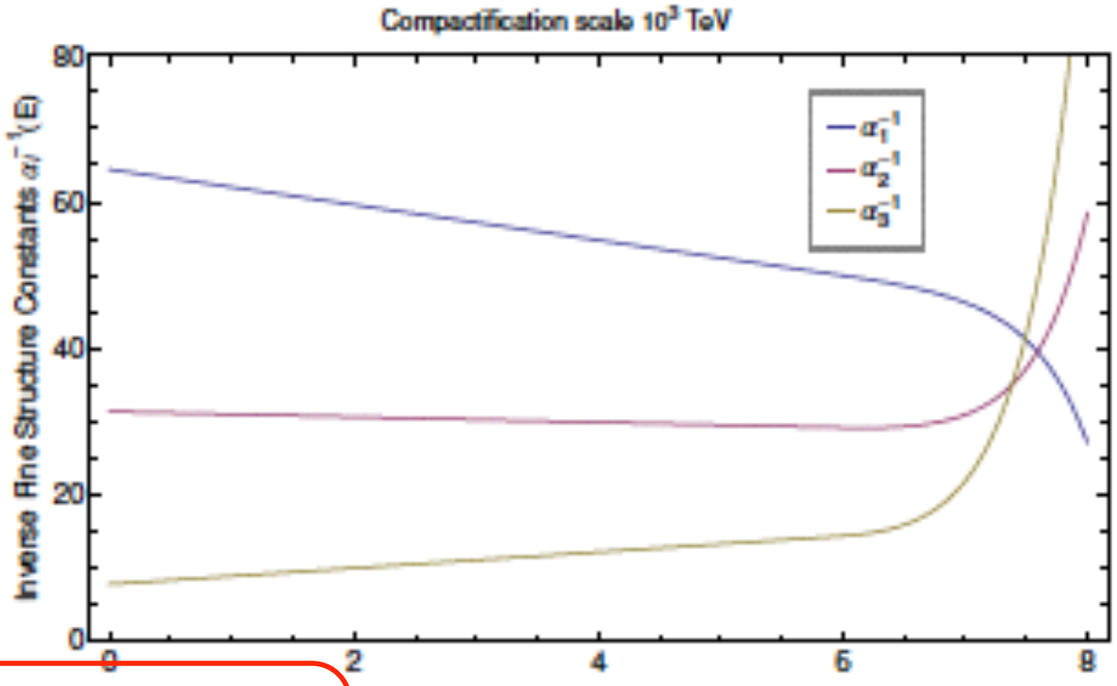
In 5D you can!



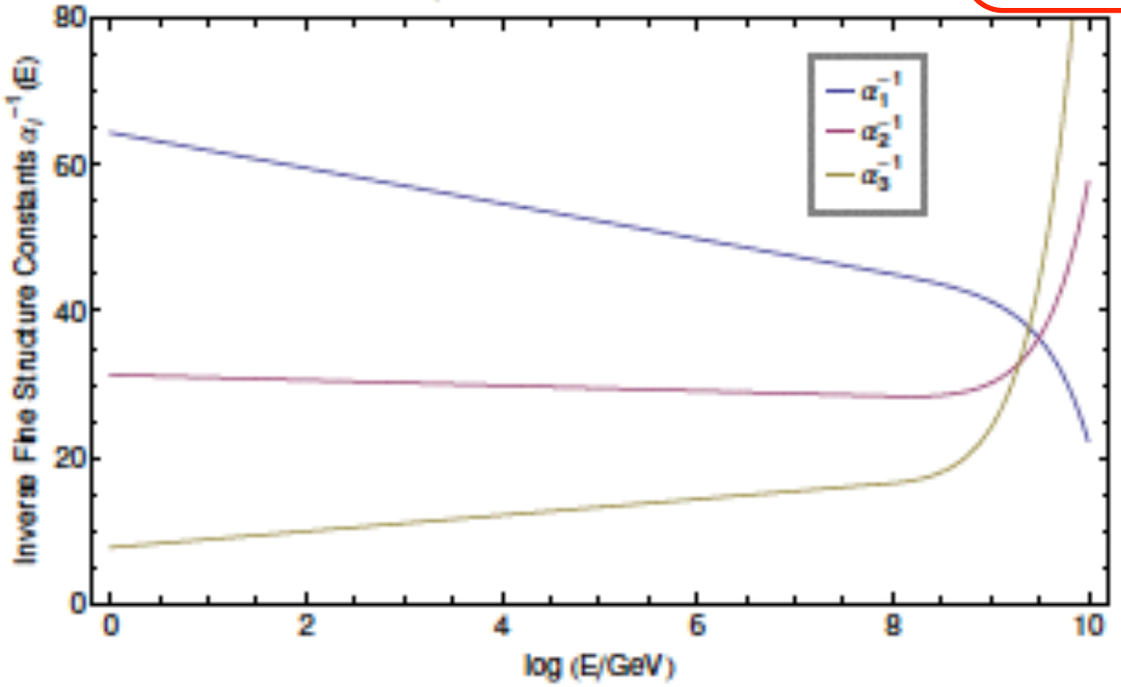
An extra dimension of radius R.
Additional Kaluza Klein modes enter RGEs @ Q> 1/R

Compactification scale 10 TeV





Unification @ 10^6 TeV



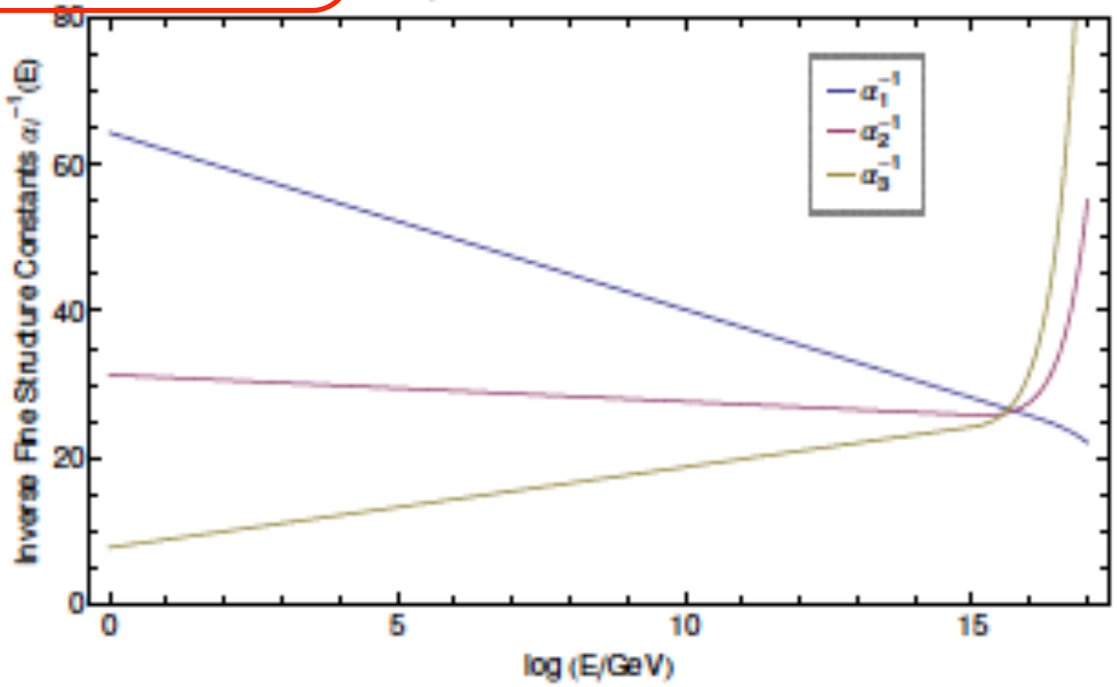


Figure 1. *Running of the inverse fine structure constants $\alpha^{-1}(E)$, for three different values of the compactification scales 10 TeV (top left panel), 10^3 TeV (top right), 10^5 TeV (bottom left) and 10^{12} TeV (bottom right), with M_3 of 1.7 TeV, as a function of log(E/GeV).*

Compactification scale 10 TeV

Compactification scale 10^3 TeV

Large splitting here

small splitting here

Flavour hierarchy just an RGE effect?

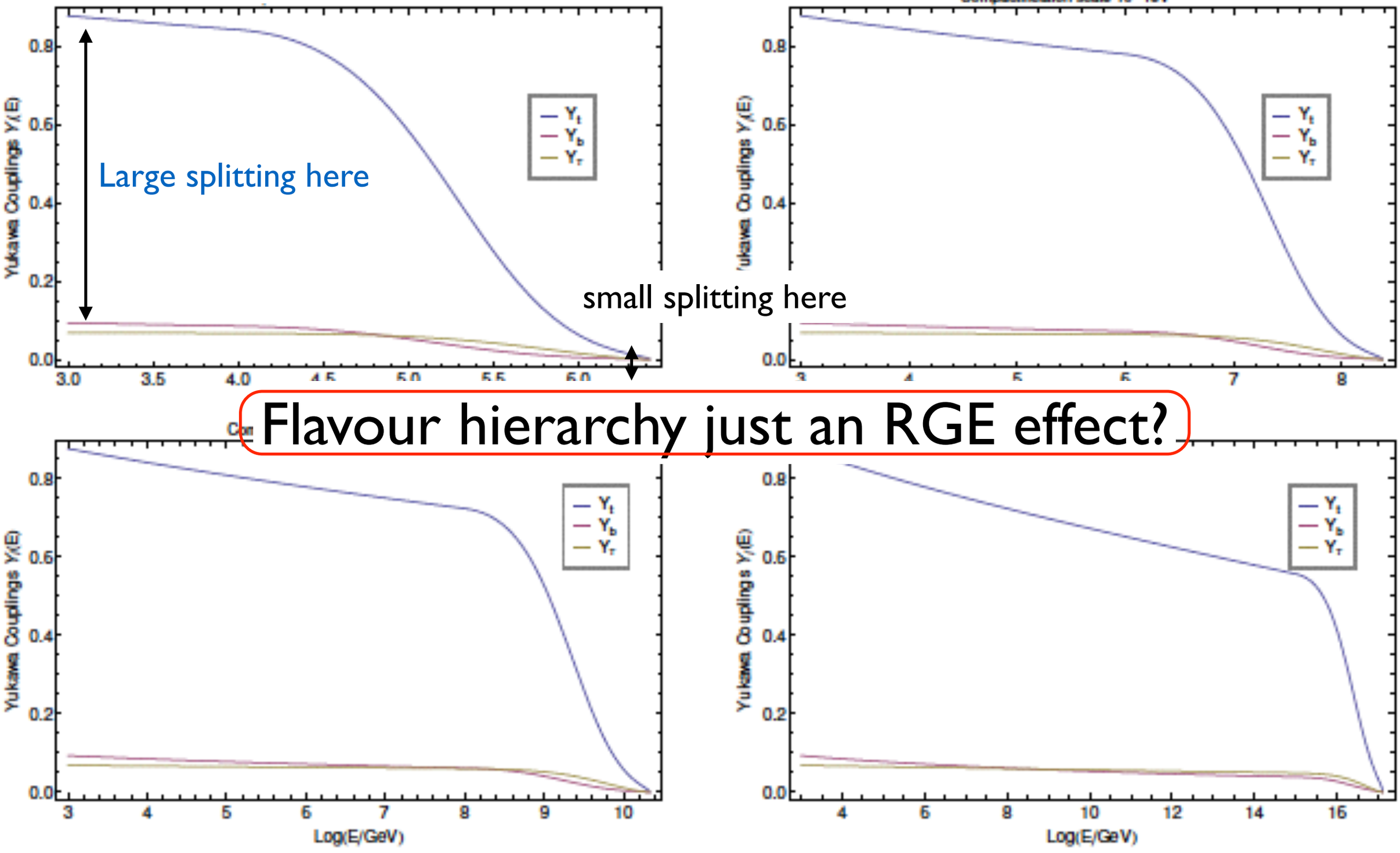
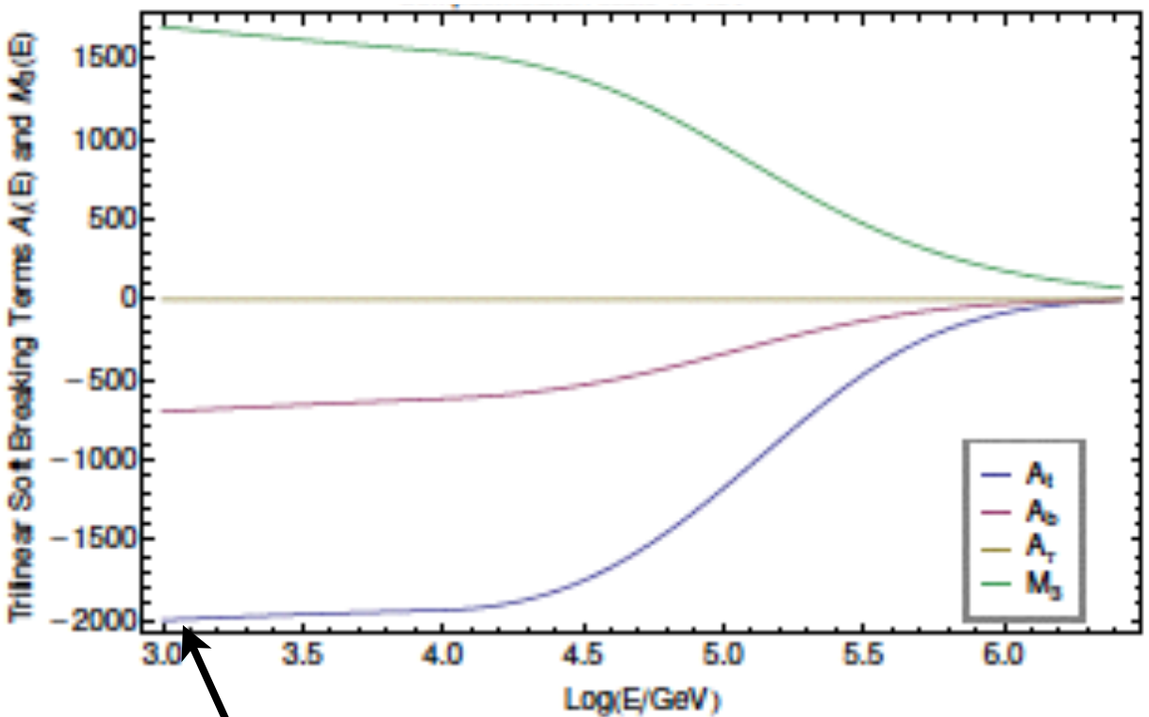
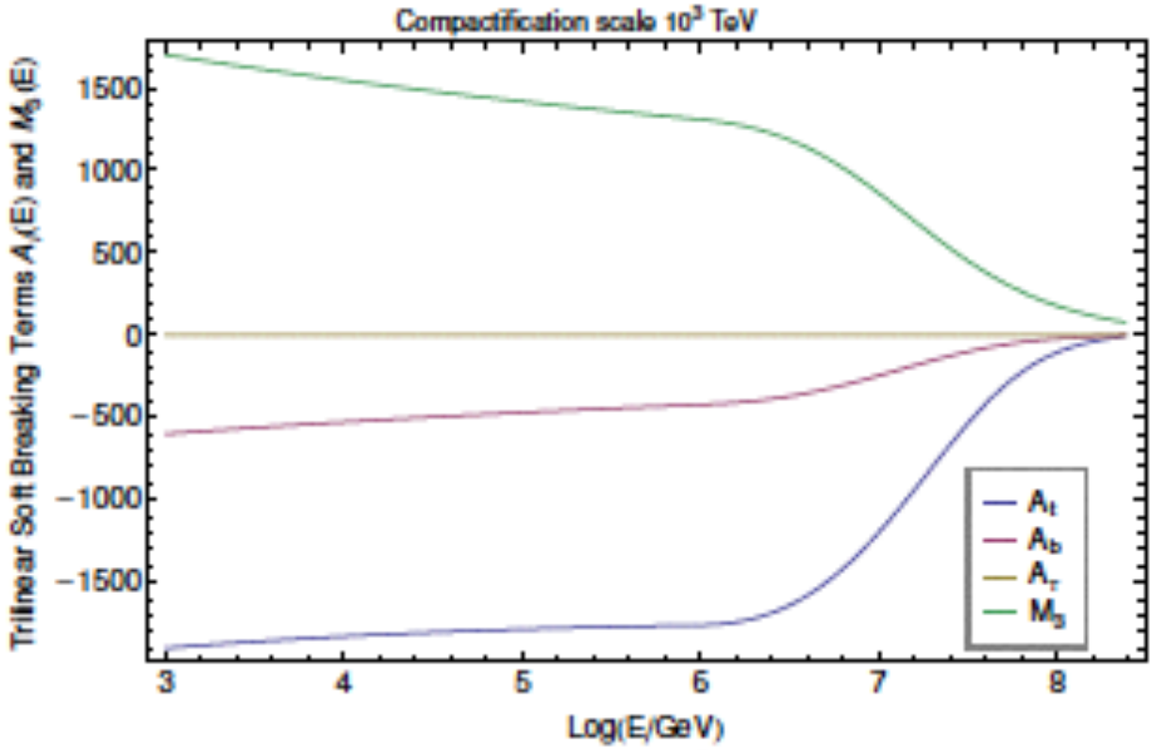
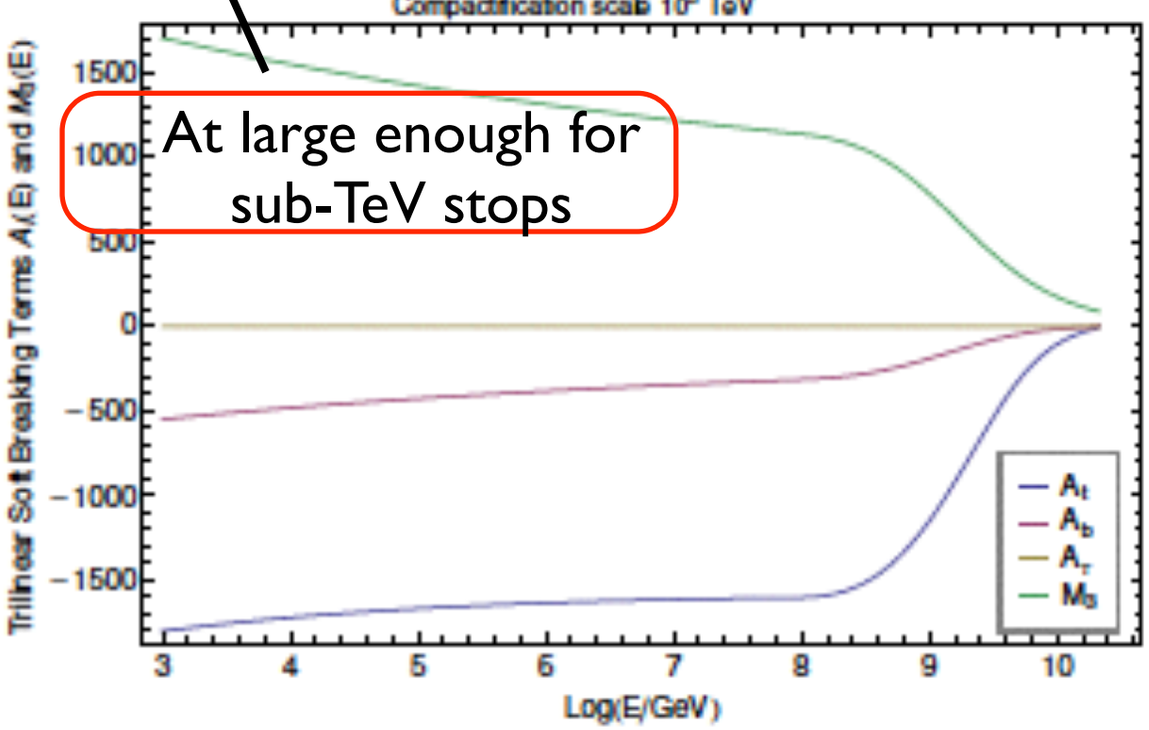


Figure 2. *Running of Yukawa couplings Y_i, for three different values of the compactification scales: 10 TeV (top left panel), 10^3 TeV (top right), 10^5 TeV (bottom left) and 10^{12} TeV (bottom right), with $M_3[10^3]$ of 1.7 TeV, as a function of log(E/GeV).*

Compactification scale 10 TeV







At large enough for sub-TeV stops

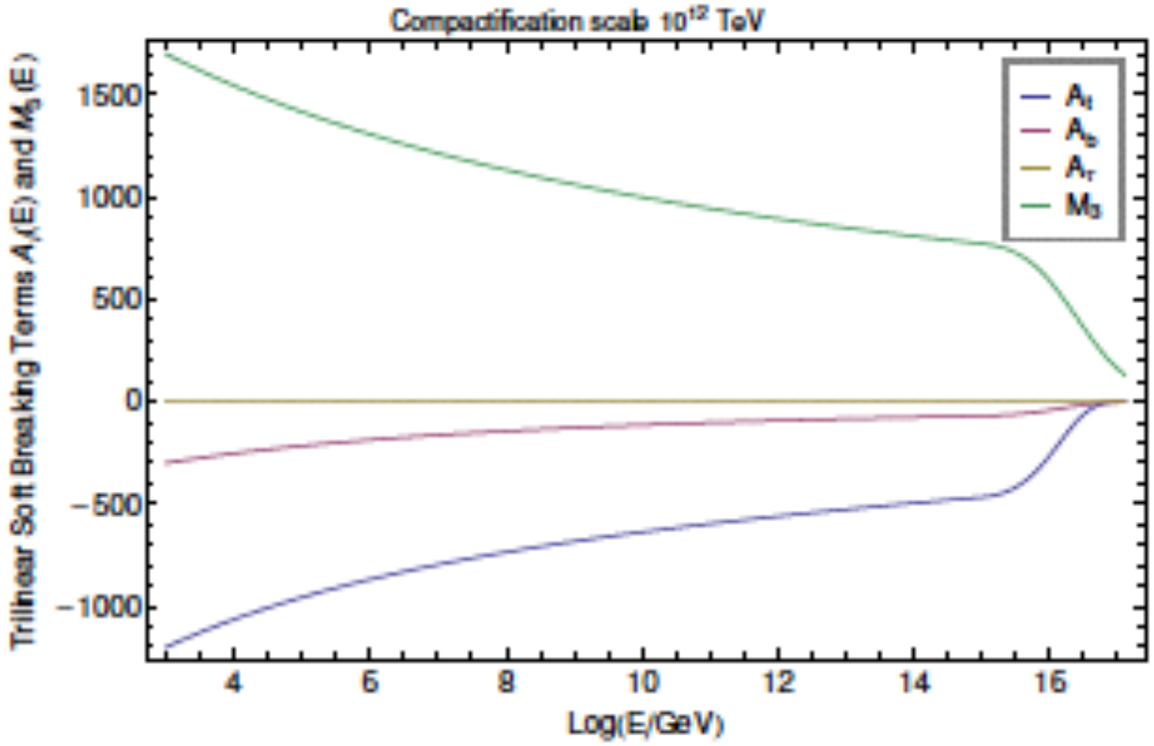
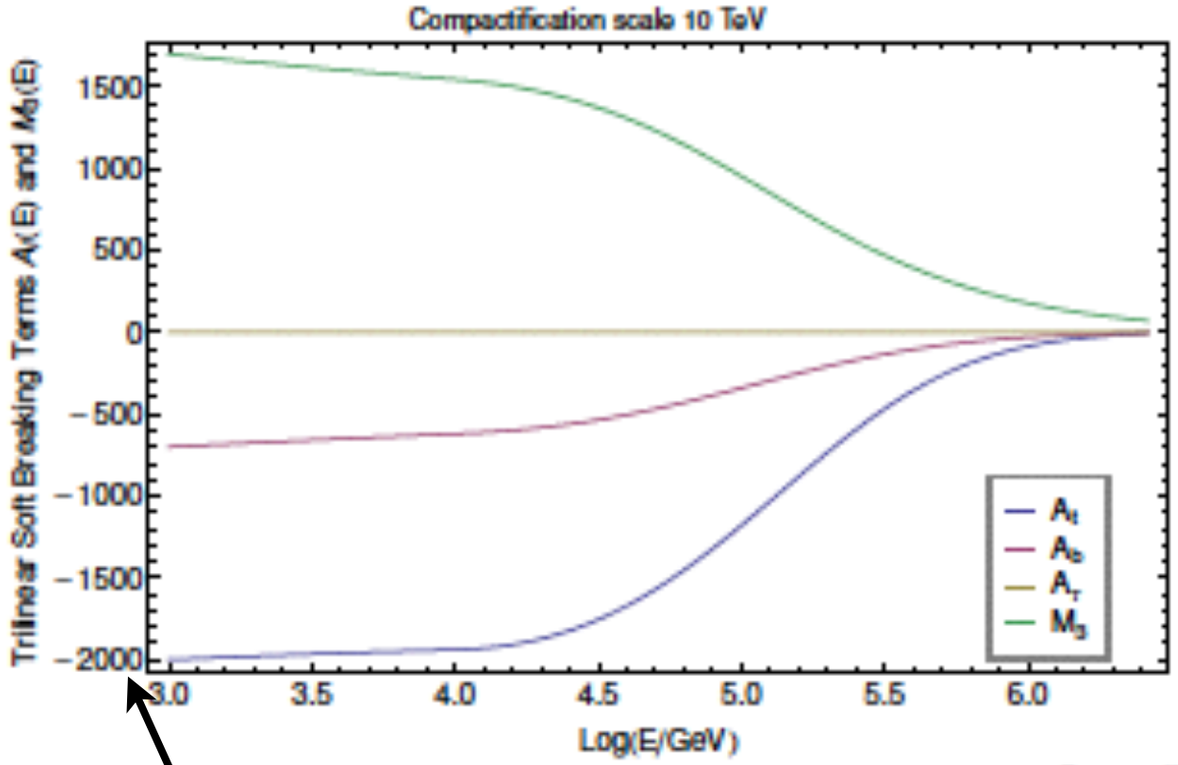
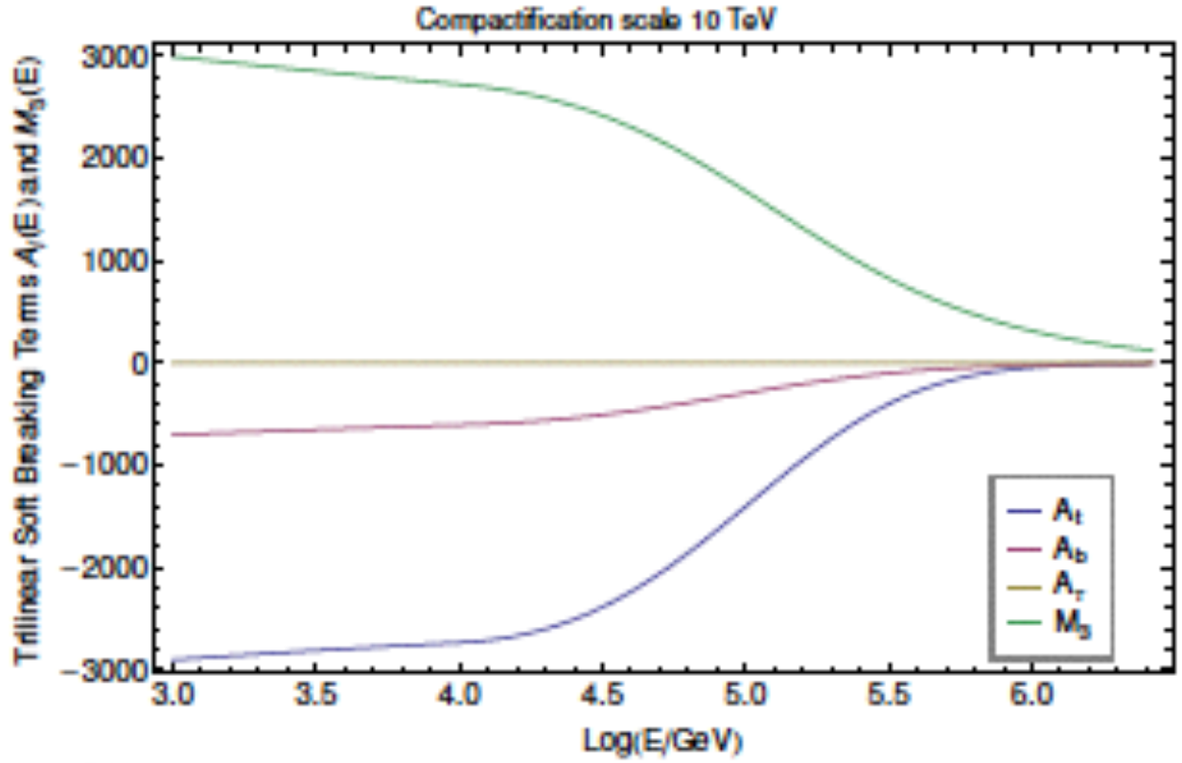
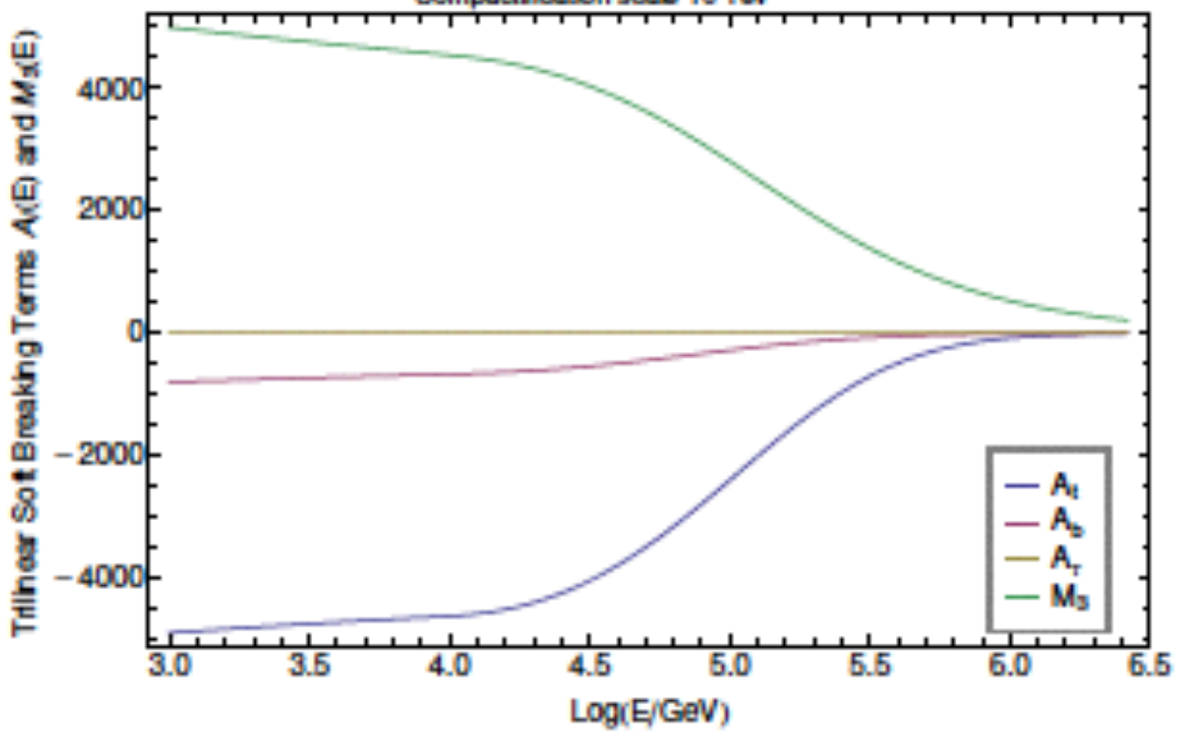


Figure 3. *Running of trilinear soft terms $A_i(3,3)(E)$, for three different values of the compactification scales 10 TeV (top left panel), 10^3 TeV (top right), 10^5 TeV (bottom left) and 10^{12} TeV (bottom right), with $M_3[10^3]$ of 1.7 TeV, as a function of log(E/GeV).*





At large enough for sub-TeV stops



Larger gluino gives larger At

Additional slides follow

Non decoupled D-terms for a 126 GeV Higgs

Moritz McGarrie
with Aoife Bharucha & Andreas Goudelis
Arxiv:1310:4500

1. The Higgs mass 126 GeV

The MSSM at one-loop

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

top mass

average stop mass

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

- 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 +....

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

stop mixing

Fine tuning: little hierarchy problem

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

Light Higgsino

For a natural cancellation these should be of the same order

Light stops

$$\delta m_{H_u}^2 \sim -\frac{3y_t^2 m_{\tilde{t}}^2}{4\pi^2}\mathrm{Log}\left(\frac{\Lambda}{m_{\tilde{t}}}\right) - \frac{3g^2}{8\pi^2}(m_{\tilde{W}}^2 + m_{\tilde{h}}^2)\mathrm{Log}(\frac{\Lambda}{m_{\tilde{W}}})$$

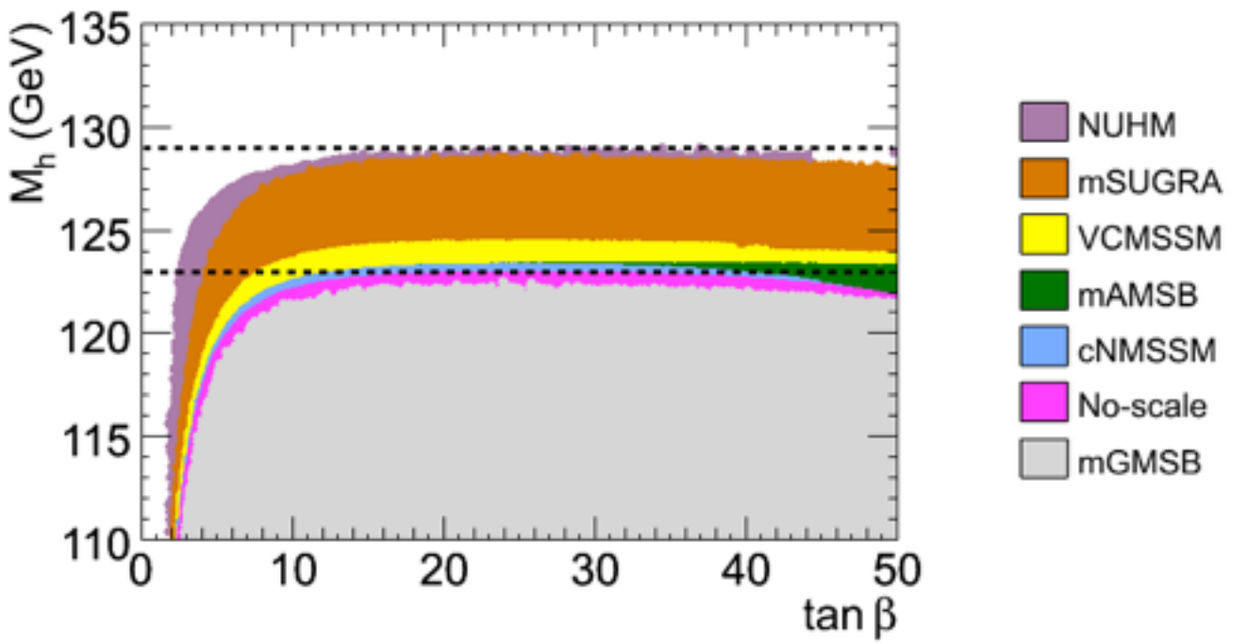
Light wino

Light(ish) Gluino

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

Fine tuning (absence of new physics)
appears all models in some way: R-S, composite Higgs, little Higgs, SUSY etc

How do benchmark (minimal) models fair?



1207.1348
Arbey, Battaglia, Djouadi, Mahmoudi

stops less than 2 TeV

The point is that these models all work, but only if the spectrum is very heavy e.g. 5-10 TeV stops: *unnatural and unobservable at LHC14.*

if you give up on naturalness, is there any reason to see anything at the LHC?

Reasons to (still) believe in SUSY

- Solves big hierarchy problem M_{EW}/M_{Pl}
- Improves GUT unification (and so too, stability of Proton)
- necessary for string theory (unification of all forces)
- radiatively induced EWSB in MSSM-like models.
- Believable dark matter candidate(s)
- It is consistent with low energy EW observables
- Improves fit to muon magnetic moment etc.
- MSSM bounds Higgs < 135 GeV

what are our choices?

The trivial *option*

Split SUSY, some landscape (multiverse) gives an explanation for Yu, Λ_{cc}, m_h^2 (maybe more?)

The hard / ugly / *unlikely option*

Generate a large At

(vanishing in mGMSB, uncalculable in SUGRA.)

although see :"Large At Without the Desert", ArXiv: 1405.1038

The innovative *option*

non-minimal….get creative....

In this talk I am going to give 2 examples of models that improve naturalness

Non decoupled D-terms
(Aoife Bharucha, Andreas Goudelis & MM) 1310.4500

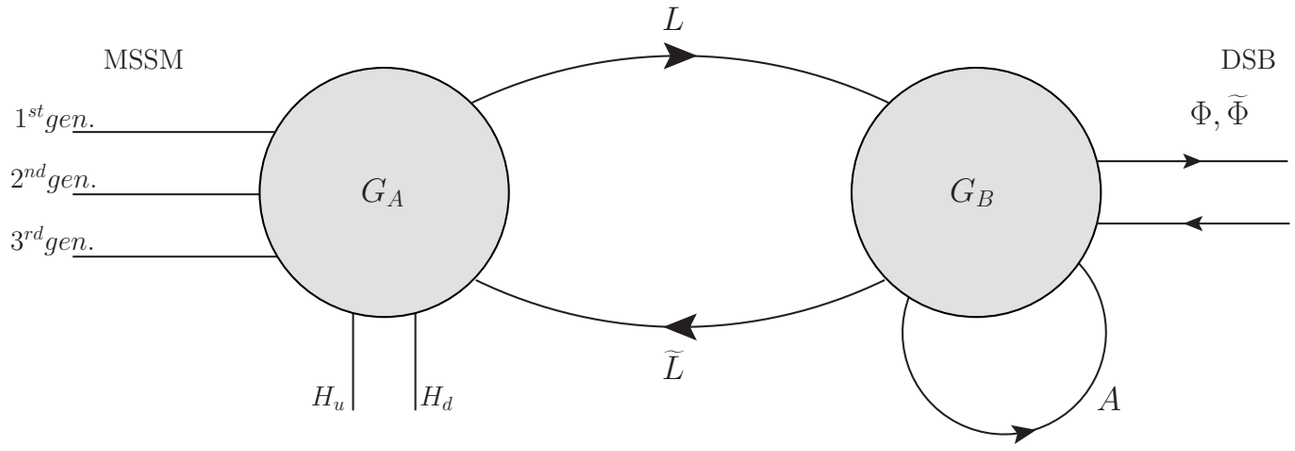
ISS & Flavour Gauge Messengers
(F.Bruemmer, A.Weiler & MM) 1312.0935
(S.Abel & MM) 1404.1318

and if time :"Large At Without the Desert", ArXiv: 1405.1038

(Both presented at SUSY 2013)

A quiver model: motivation

- non decoupled D-terms: lifts the Higgs (sometimes substantially) Batra, Delgado, Kaplan, Tait 0309149
- extra adjoints of SU(2),SU(3): lifts the Higgs
- More natural than NMSSM?
- embeds into magnetic SQCD
- Deconstructs an extra dimension
- "Split families": Batra, Kaplan, Tait, Delgado 0404251/0409073



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

Related works:

Csaki, Erlich, Grojean, Kribs 0106044
Medina, Shah, Wagner 0904.1625

"GGM and Deconstruction"
M.M. 1009.0012 and 1101.5158

Auzzi, Giveon, Gudnason, Shacham
1009.1714
1011.1664

easyDiracGauginos

Abel, Goodsell

Bharucha, Goudelis, M.M. 1310.4500

$$\delta\mathcal{L} = -g_1^2\Delta_1(H_u^\dagger H_u - H_d^\dagger H_d)^2 - g_2^2\Delta_2\sum_a(H_u^\dagger\sigma^a H_u + H_d^\dagger\sigma^a H_d)^2$$

$$m_z^2 \to m_z^2 + \left(\frac{g_1^2\Delta_1 + g_2^2\Delta_2}{2}\right)v_{ew}^2$$

D-terms Vs NMSSM

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

$$\Delta = (\frac{g_A^2}{g_B^2})\frac{2m_L^2}{m_v^2 + 2m_L^2}$$

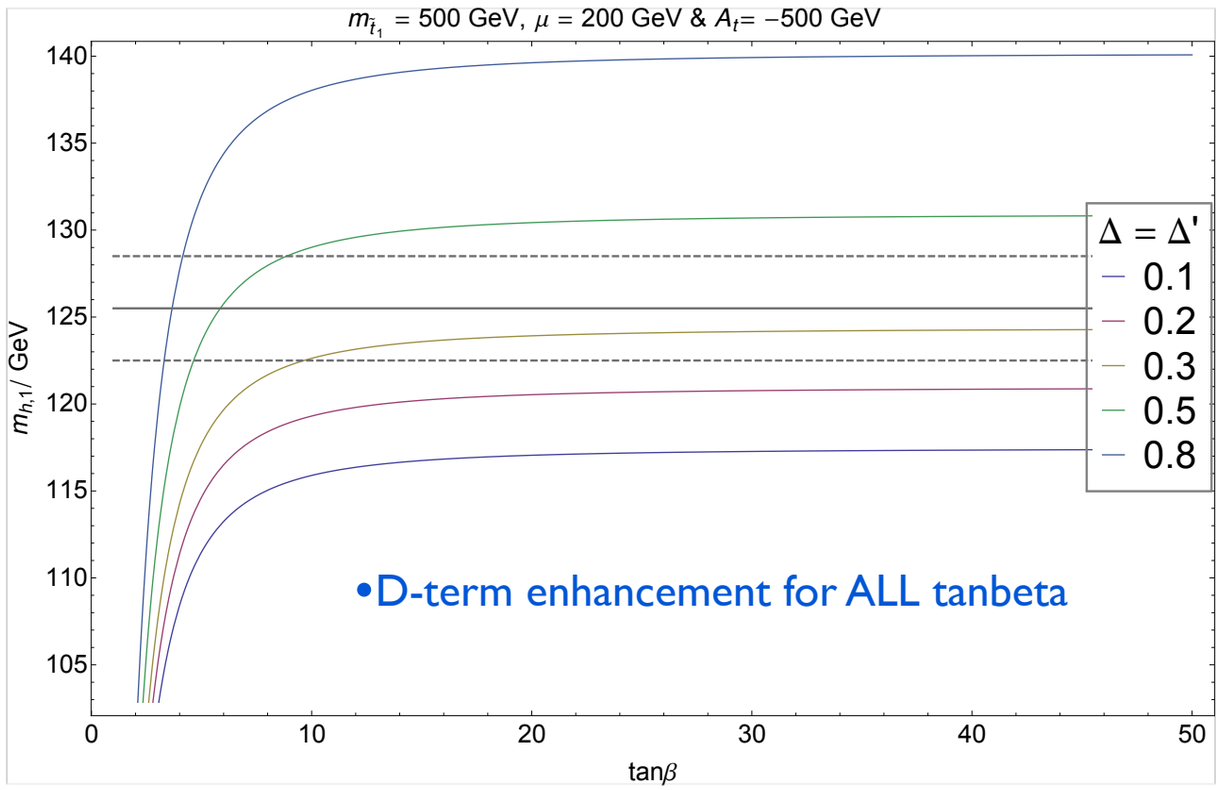
$$\delta\mathcal{L} = -g_1^2\Delta_1(H_u^\dagger H_u - H_d^\dagger H_d)^2 - g_2^2\Delta_2\sum_a(H_u^\dagger\sigma^a H_u + H_d^\dagger\sigma^a H_d)^2$$

$$m_z^2 \to m_z^2 + \left(\frac{g_1^2\Delta_1 + g_2^2\Delta_2}{2}\right)v_{ew}^2$$

$$W_{NMSSM} \supset \lambda S H_u H_d$$

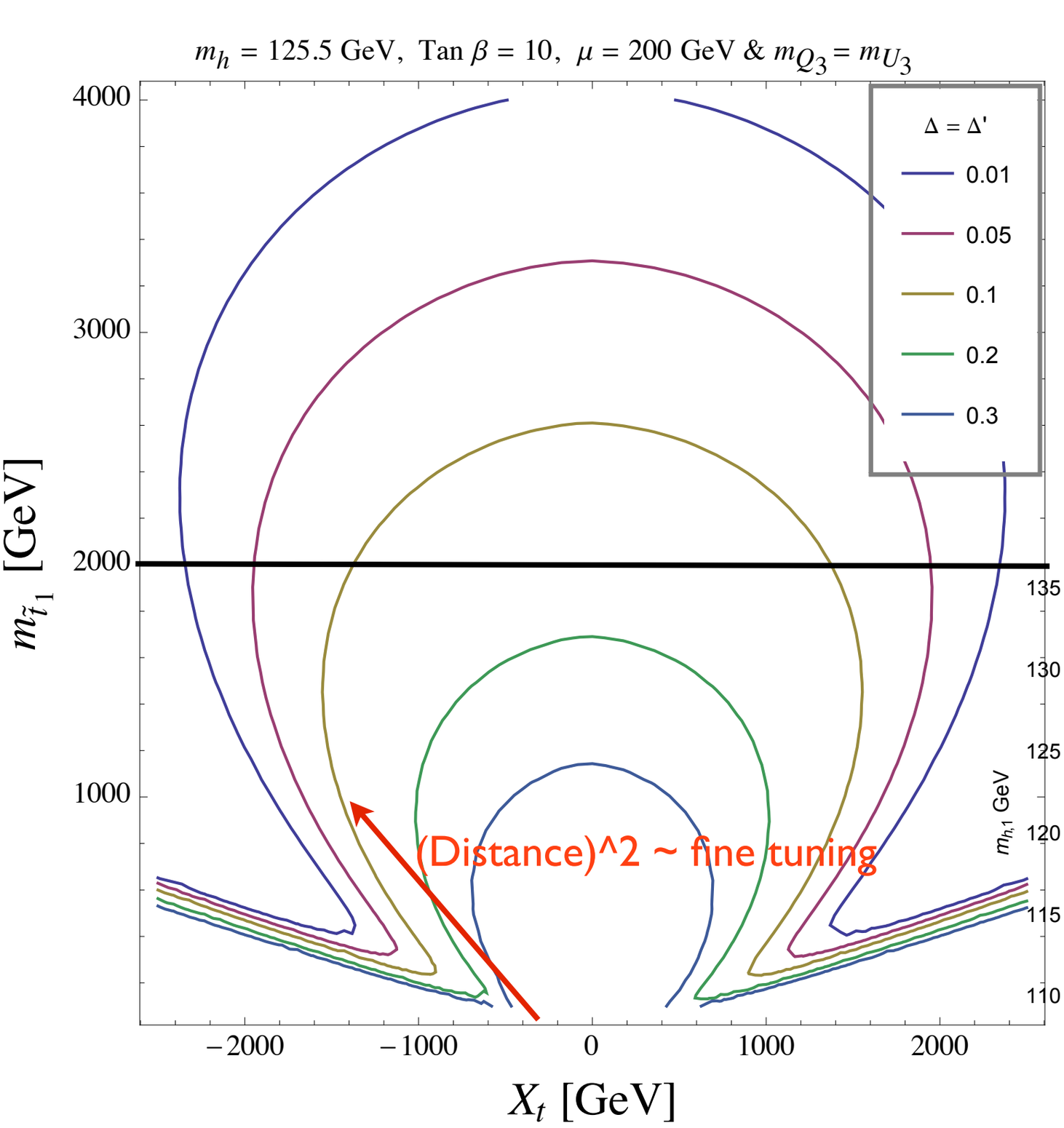
$$V(\phi's) \supset \lambda^2|H_u H_d|^2$$

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

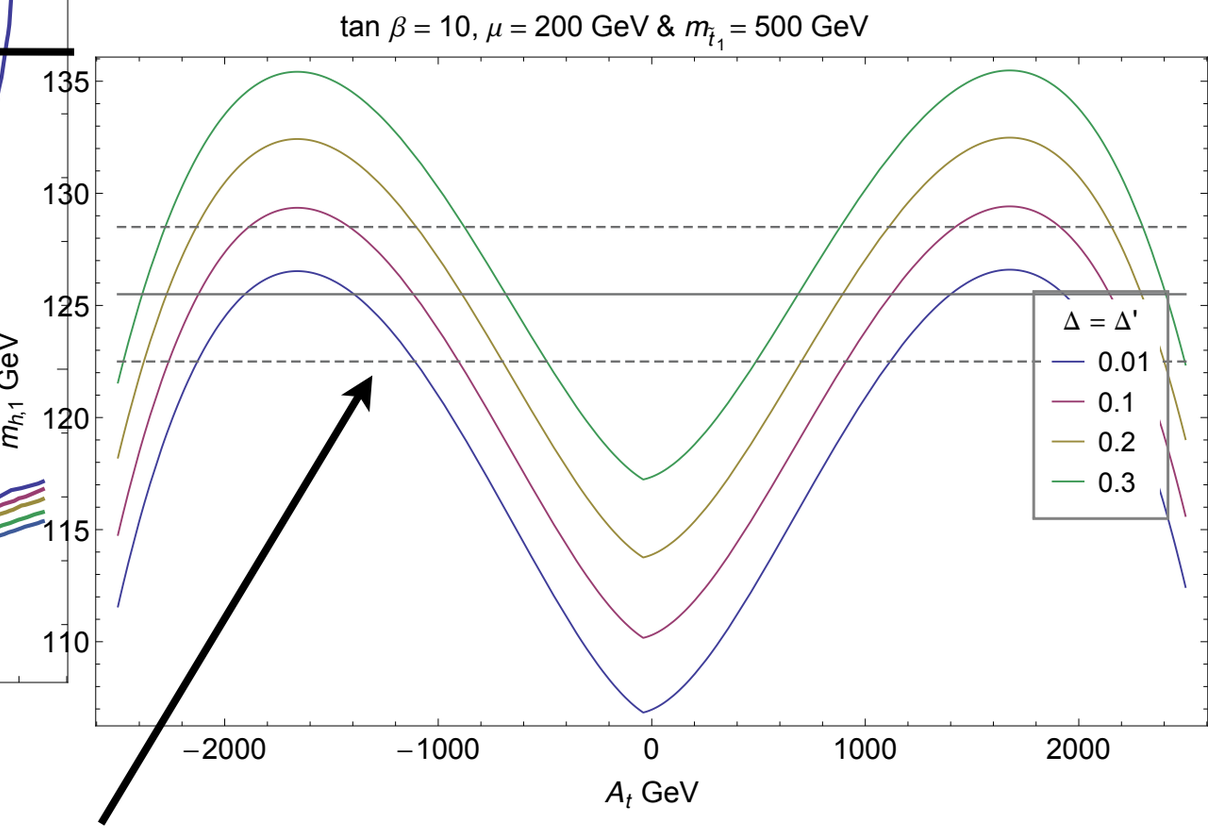


- D-term enhancement for ALL tanbeta
- F-term enhancement only for small tanbeta

M.M. Moortgat-Pick & S.Porto, G.



Sub 2 TeV stops for $\Delta \geq 0.1$



Combination of medium size At and Deltas can do the trick! (GMSB back in the game?)

So far most studies of D-terms have been at tree-level and bottom-up ....

A *meta* model

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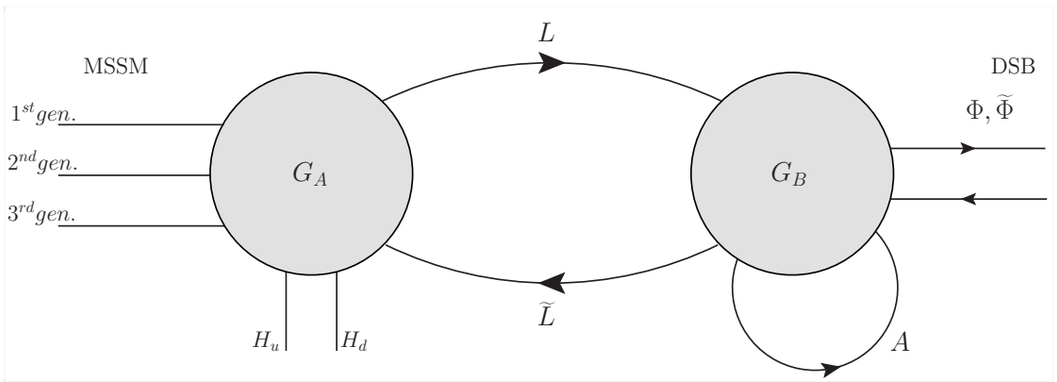
SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)_A, \mathrm{SU}(2)_B, \mathrm{SU}(3)_c, U(1)_B, \mathrm{SU}(2)_A)$	R-Parity
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{1}, \mathbf{3}, 0, \mathbf{2})$	-1
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{1}, \mathbf{1}, 0, \mathbf{2})$	-1
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{1}, \mathbf{1}, 0, \mathbf{2})$	$+1$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{1}, \mathbf{1}, 0, \mathbf{2})$	$+1$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}}, 0, \mathbf{1})$	-1
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}}, 0, \mathbf{1})$	-1
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, 0, \mathbf{1})$	-1
$\hat{L}$	L	ψ_L	1	$(-\frac{1}{2}, \overline{\mathbf{2}}, \mathbf{1}, \frac{1}{2}, \mathbf{2})$	$+1$
$\hat{\tilde{L}}$	$\tilde{L}$	$\psi_{\tilde{L}}$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1}, -\frac{1}{2}, \overline{\mathbf{2}})$	$+1$
$\hat{K}$	K	ψ_K	1	$(0, \mathbf{1}, \mathbf{1}, 0, \mathbf{1})$	$+1$
$\hat{A}$	A	ψ_A	1	$(0, \mathbf{3}, \mathbf{1}, 0, \mathbf{1})$	$+1$

Table 2. Matter fields of the model.



$$W_{\mathrm{SSM}} = Y_u\,\hat{u}\,\hat{q}\,\hat{H}_u - Y_d\,\hat{d}\,\hat{q}\,\hat{H}_d - Y_e\,\hat{e}\,\hat{l}\,\hat{H}_d + \mu\,\hat{H}_u\,\hat{H}_d$$

$$W_{\mathrm{Quiver}} = \frac{Y_K}{2}\hat{K}(\hat{L}\,\hat{\tilde{L}} - V^2) + Y_A\,\hat{L}\,\hat{A}\,\hat{\tilde{L}}$$

The most sophisticated model so far implemented into a spectrum generator (SARAH/SPHENO)
A *meta*-model i.e. *independent* of the type of supersymmetry breaking:
AMSB, mSUGRA, GMSB, phenomenological, other?

Building a taylor made spectrum generator!

- We used SARAH (written by Florian Staub) mathematica package: "a spectrum generator *generator*" to write our own spectrum generator.

- We implemented 5 gauge groups with full 2-loop RGE's and one loop self energies (soon 6 and 9 gauge groups!).

- Higgsing, and breaking to the diagonal 4 gauge groups, including all mixing matrices and assignment of Goldstones, Ghosts, RGEs of *vevs*, and Bmu at 2 loop.

- All 3 and 4 vertices of all fields computed, and self energies.

- All anomalous dimensions, tadpoles and running of all *additional soft terms and additional Yukawas, at 2 loop level.*

- finite shifts and threshold corrections also accounted for

- Can talk to FeynArts, FormCalc, CalcHep, Higgsignals, HiggsBounds, WHIZARD. micrOMEGAS, Vevacious and more.

Quiver @
M messenger

↓

Threshold
scale:

MSSM

↓

LHC

Same precision as SOFTSUSY, SPheno,SUSPECT

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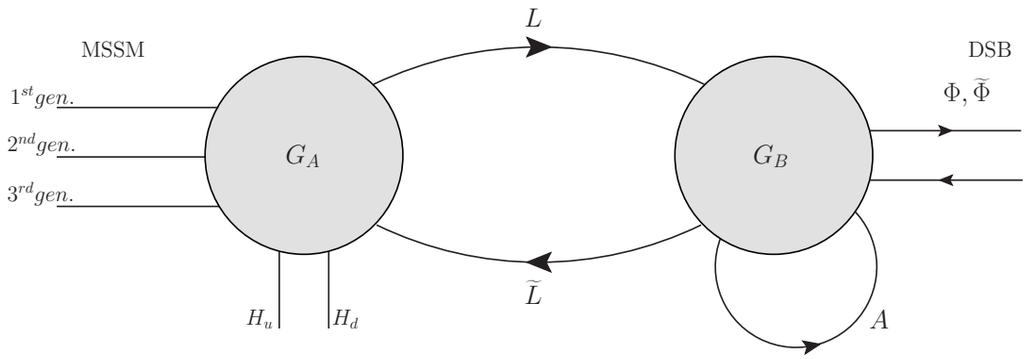
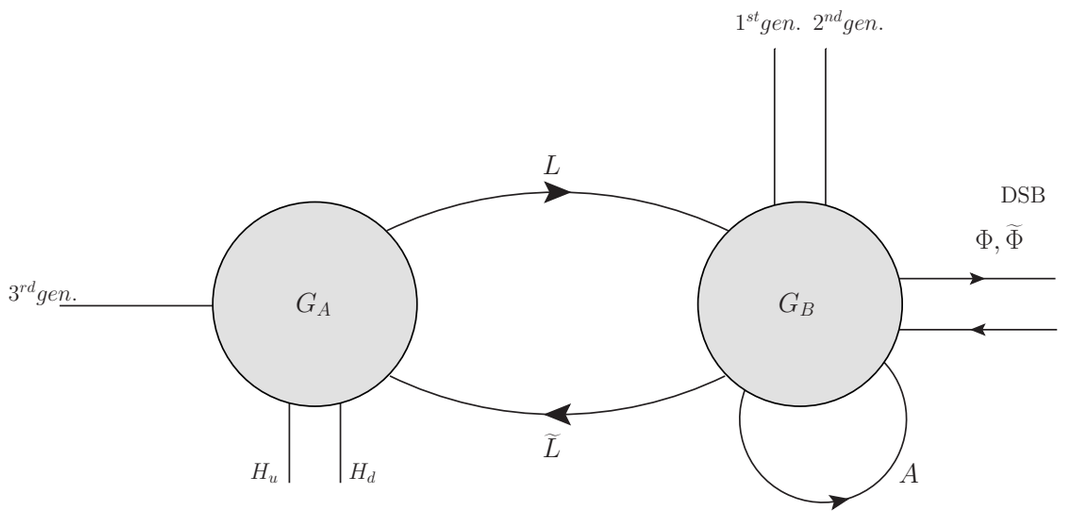
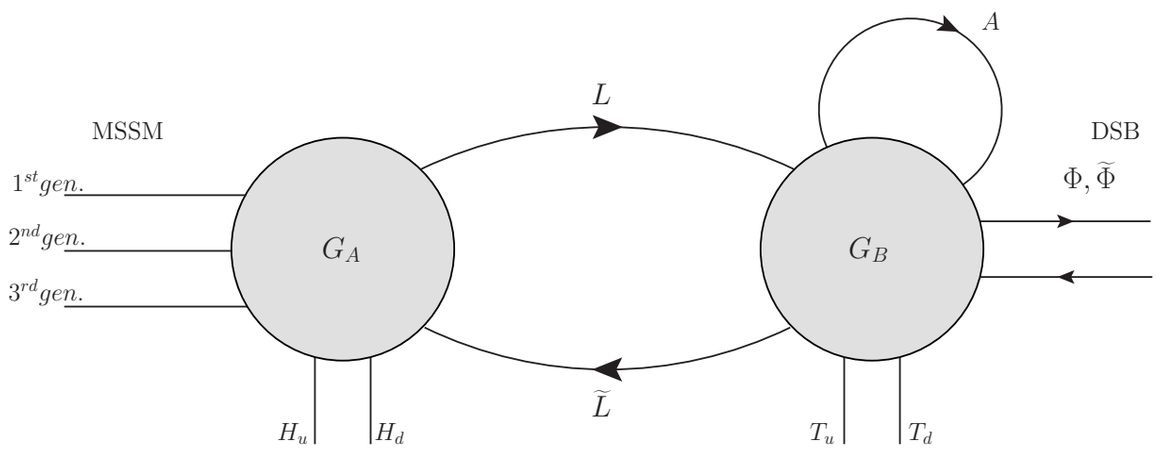
The Quiver Variations





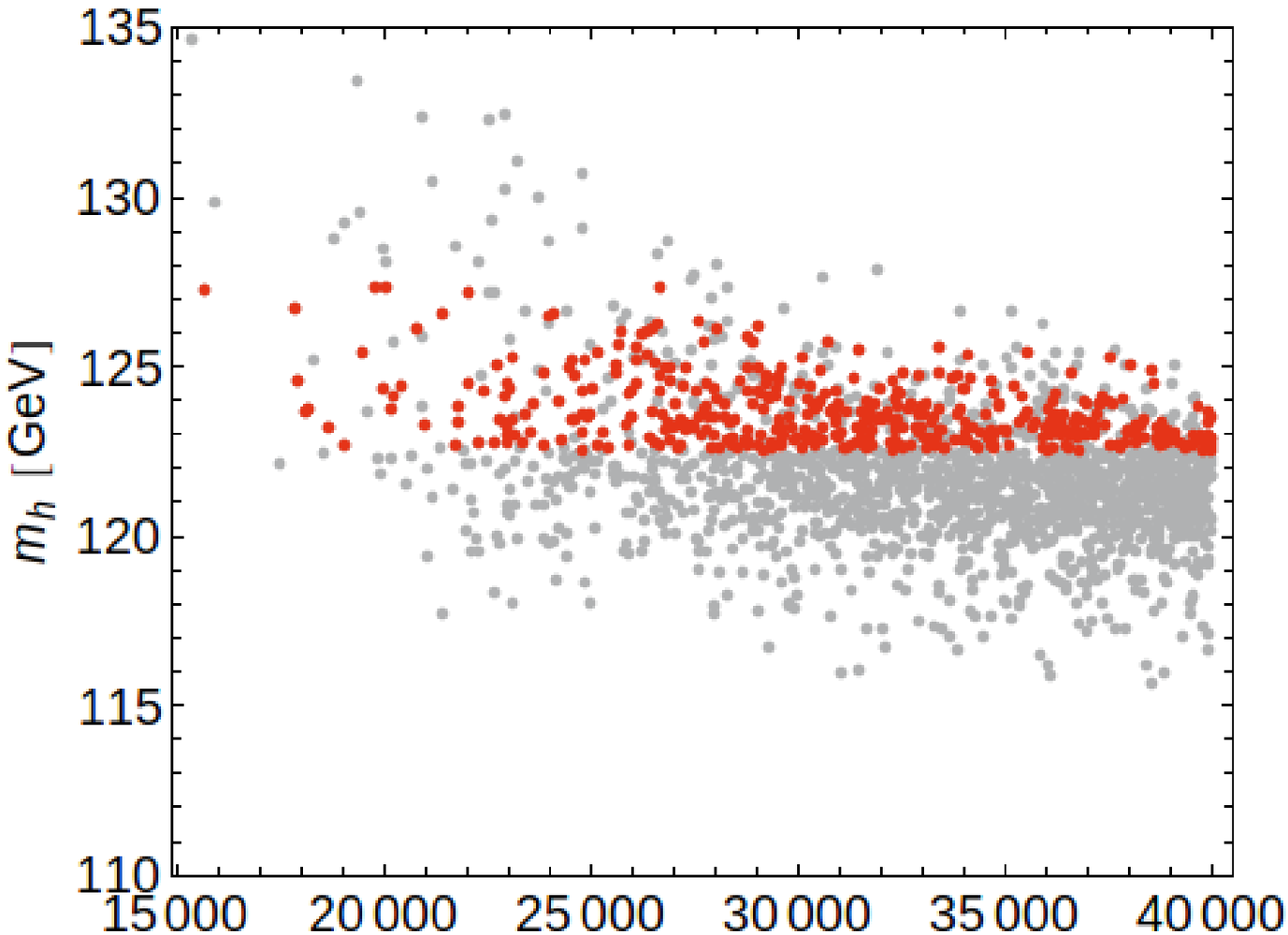


Wish list

- $v < 10\mathrm{TeV}$

$$m_L^2 > m_v^2$$

We assumed GMSB for soft terms!



Our wishes were not granted!
we had to enlarge m_L^2 to
make it work

But perhaps this can be improved by considering
different SUSY breaking scenarios

Ex. Applying mSUGRA here may get v down

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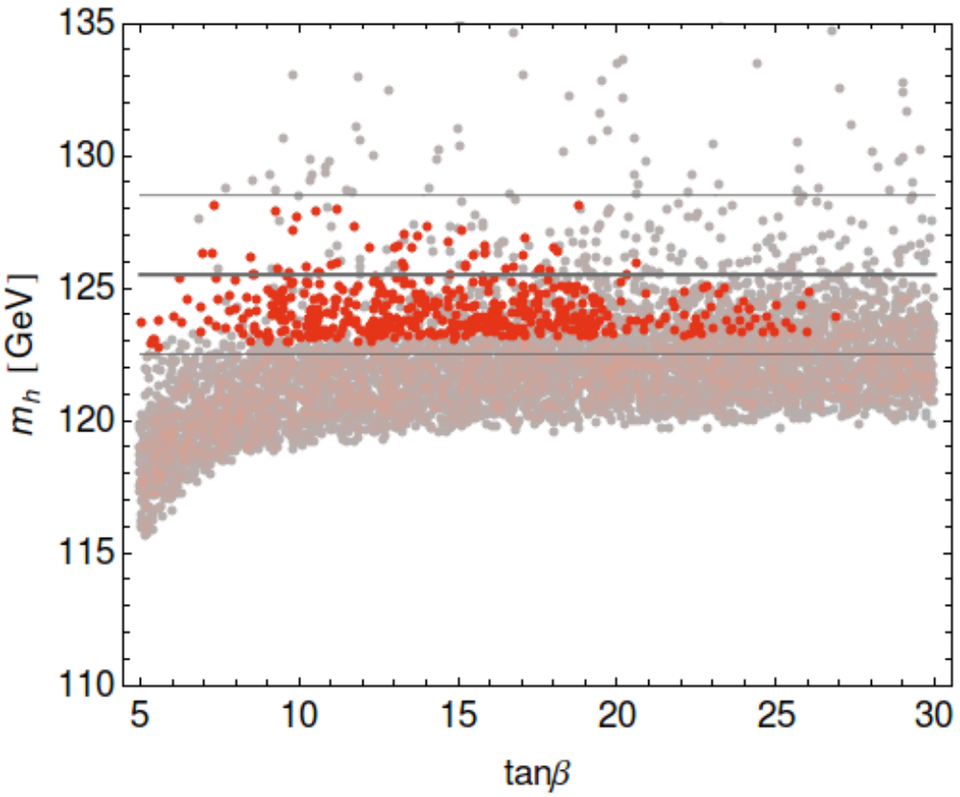

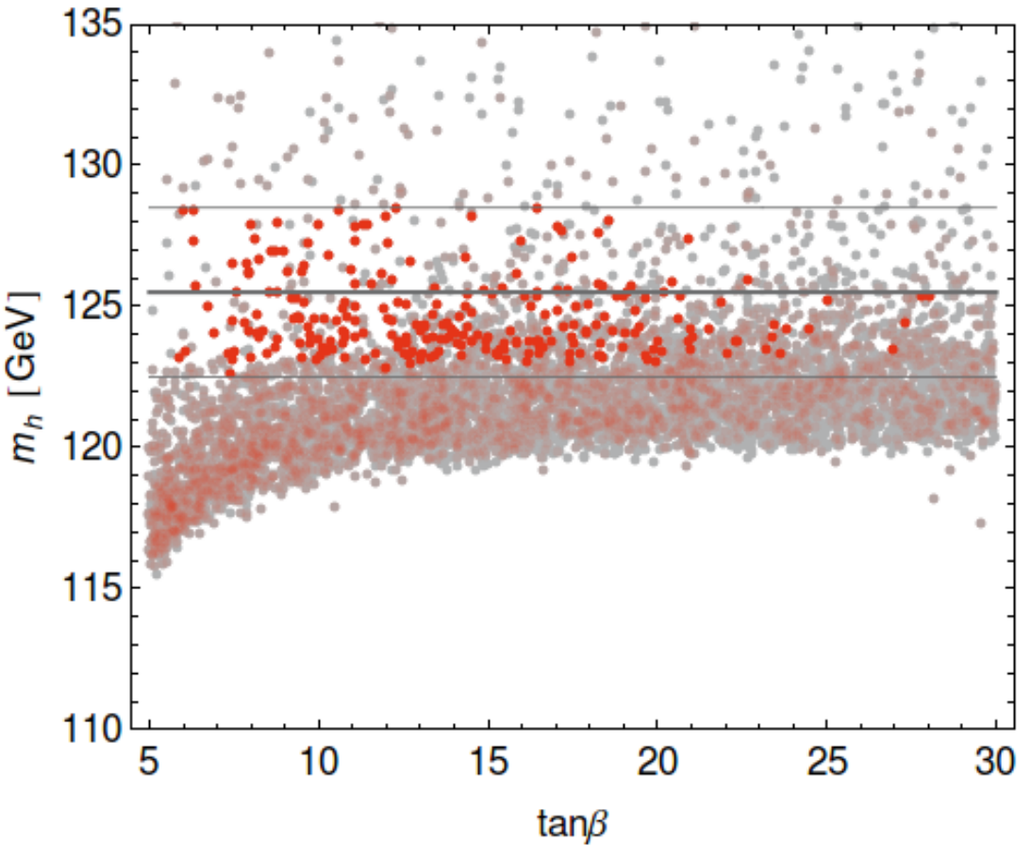

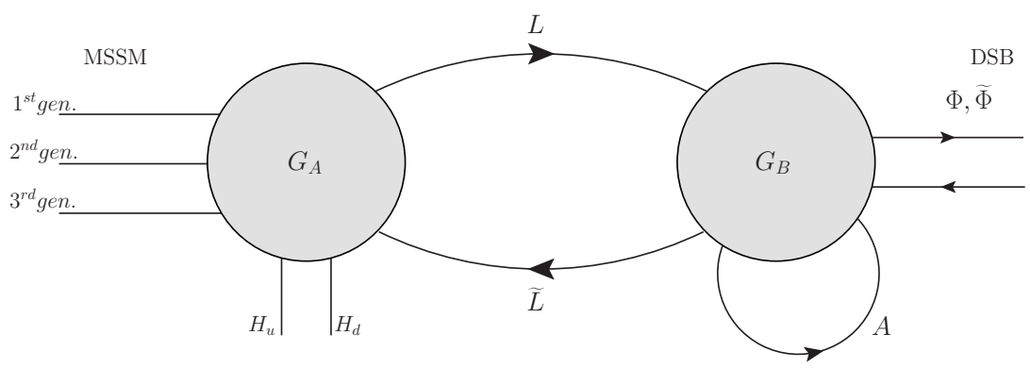

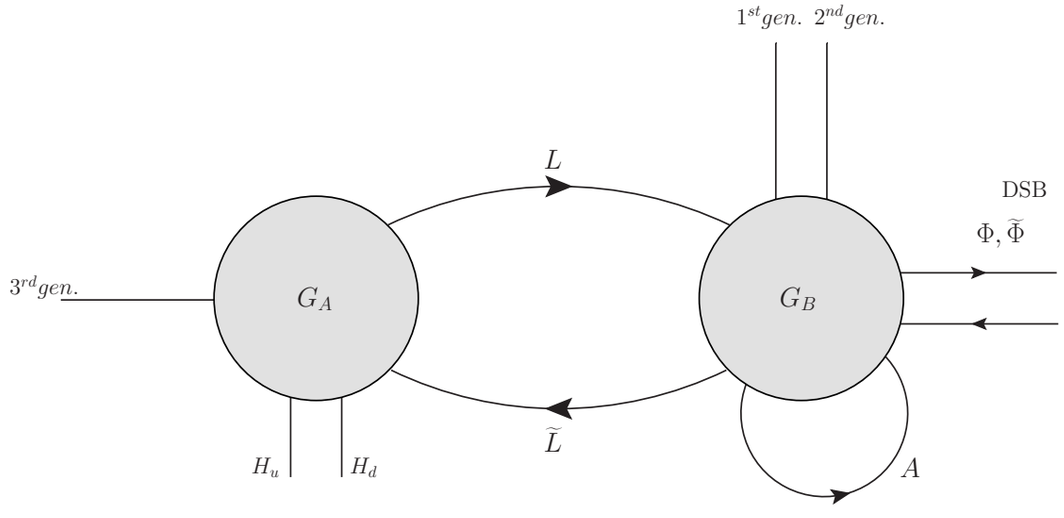

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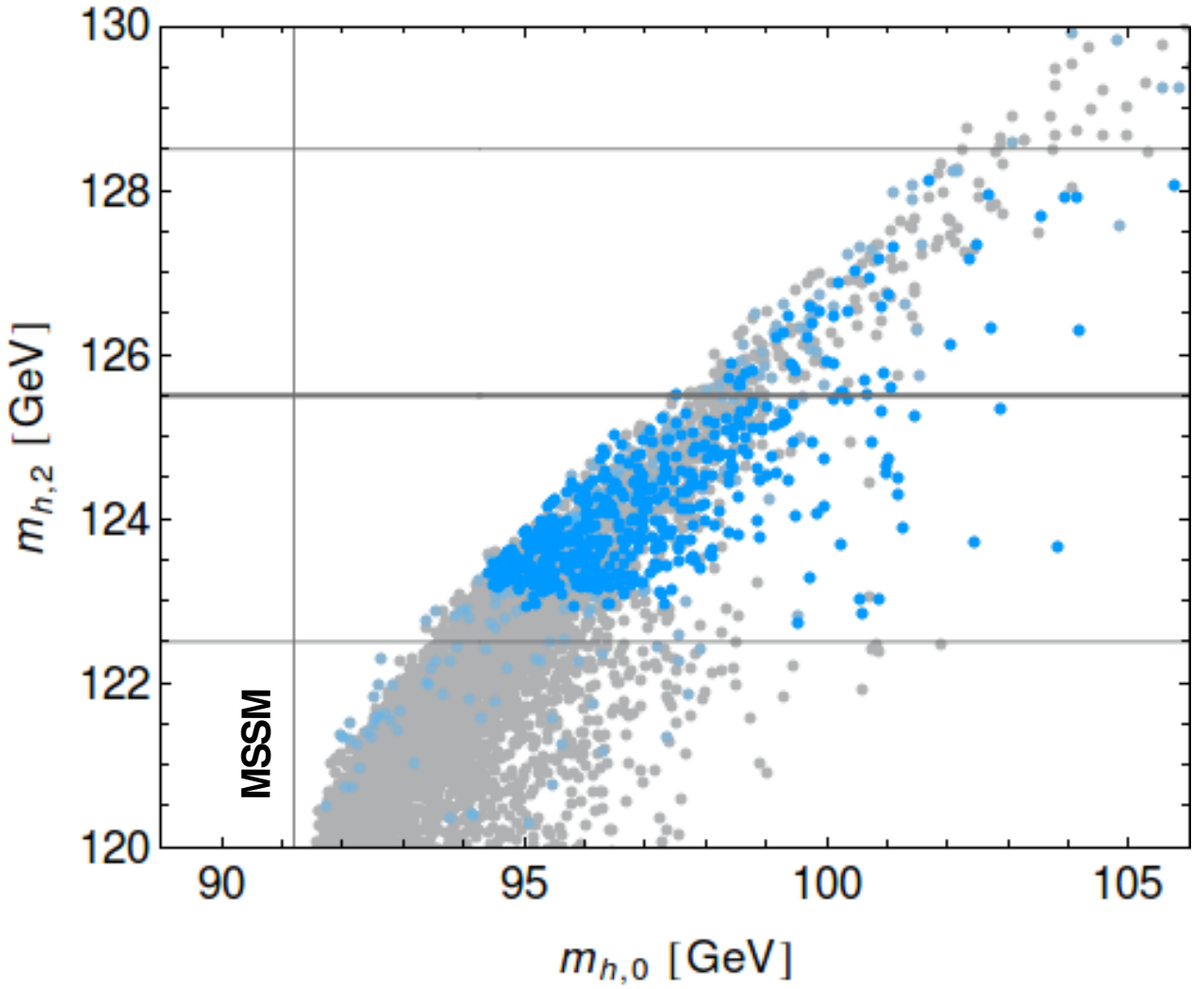
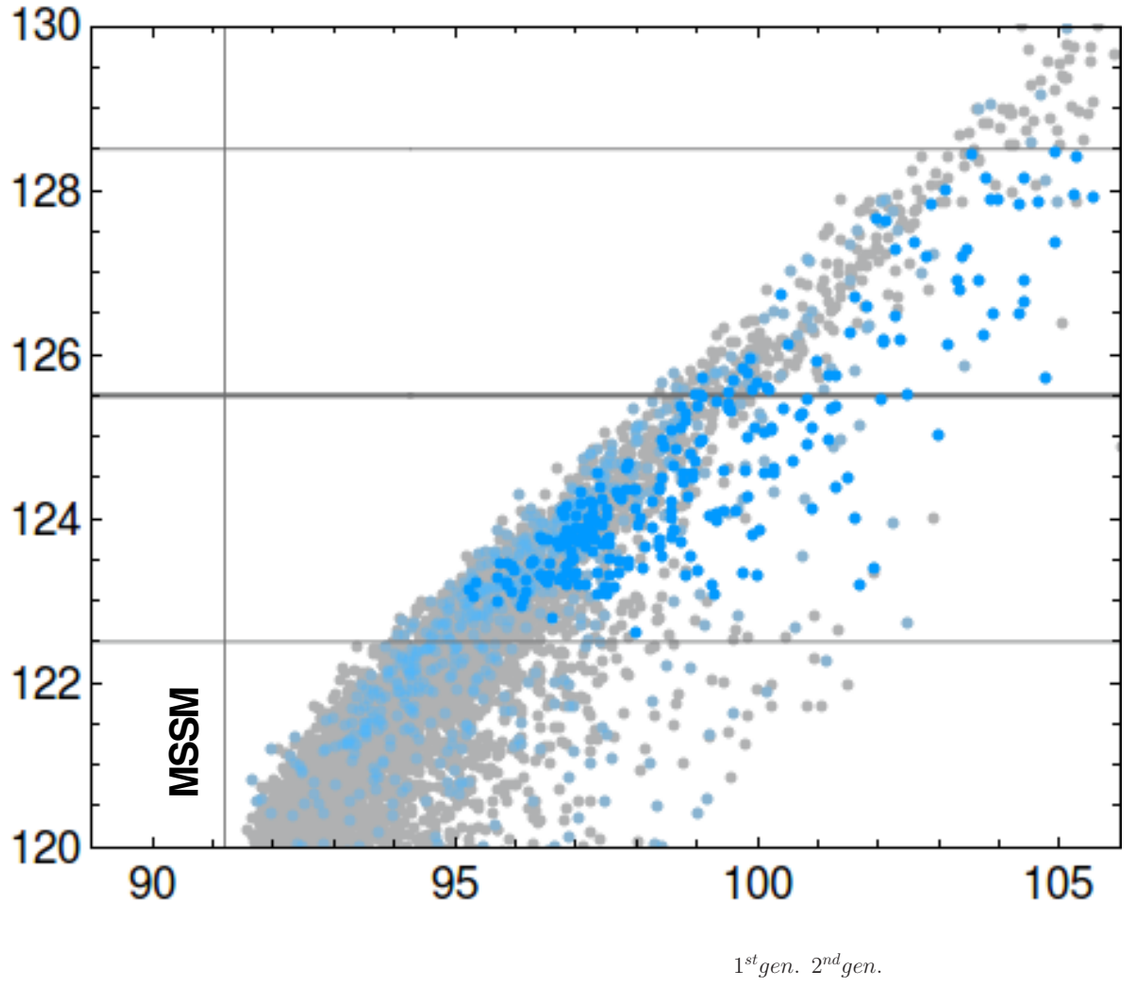
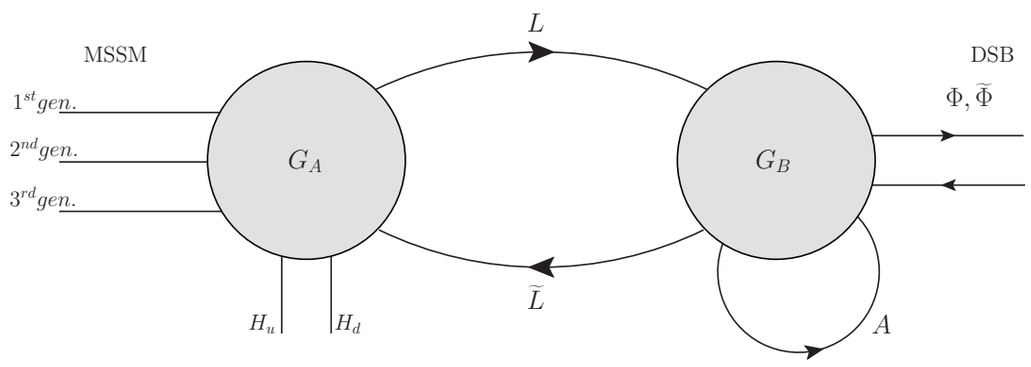
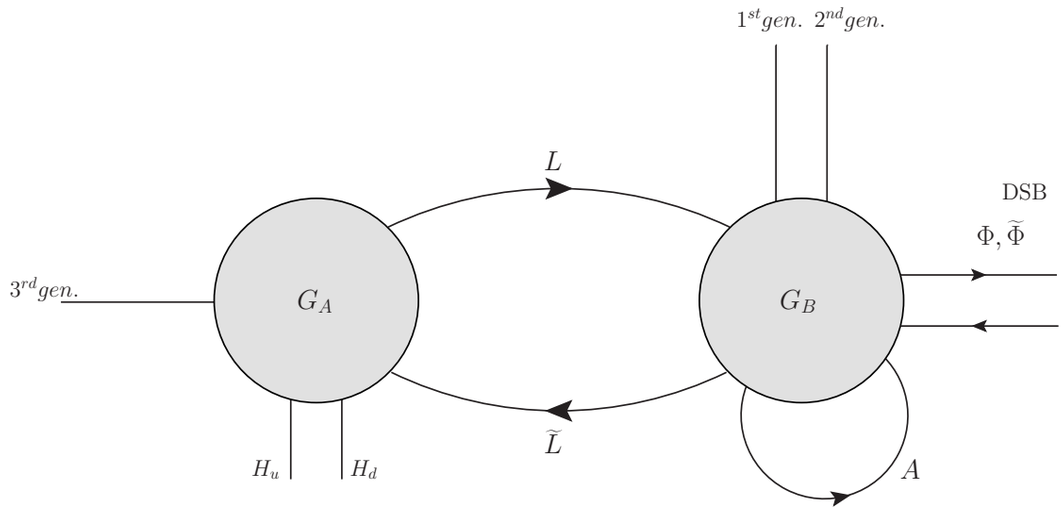
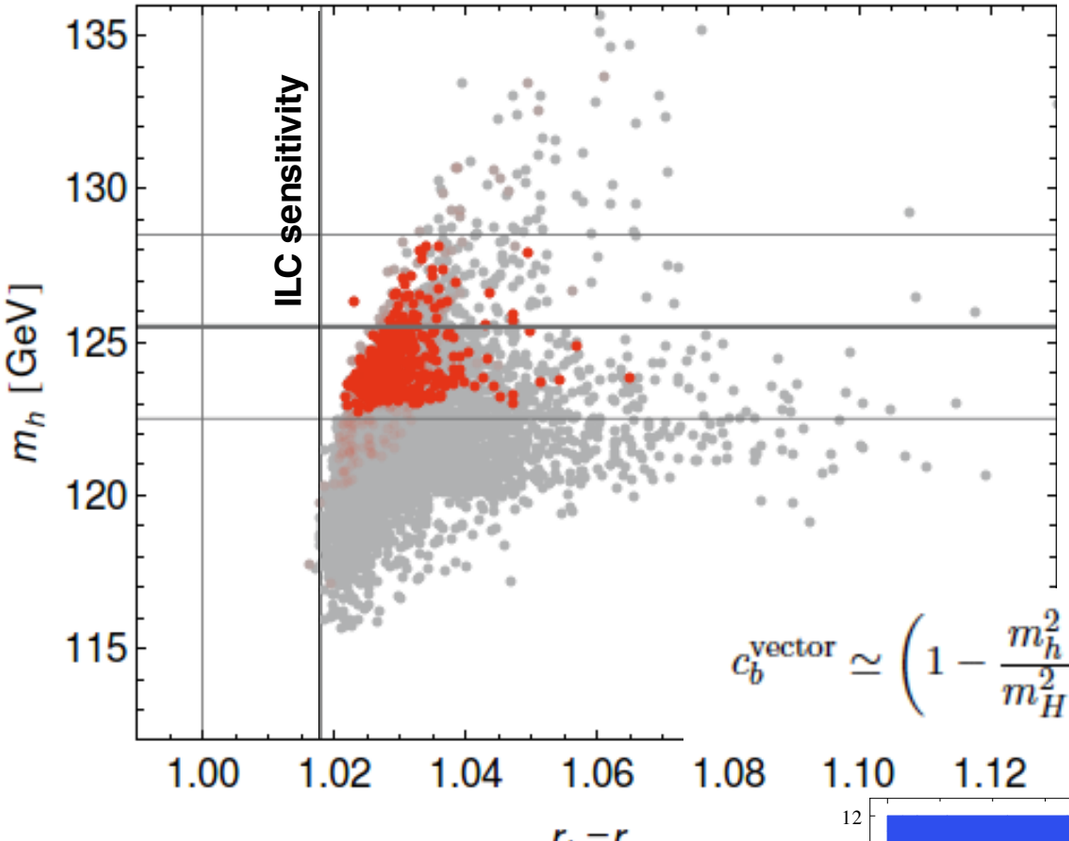




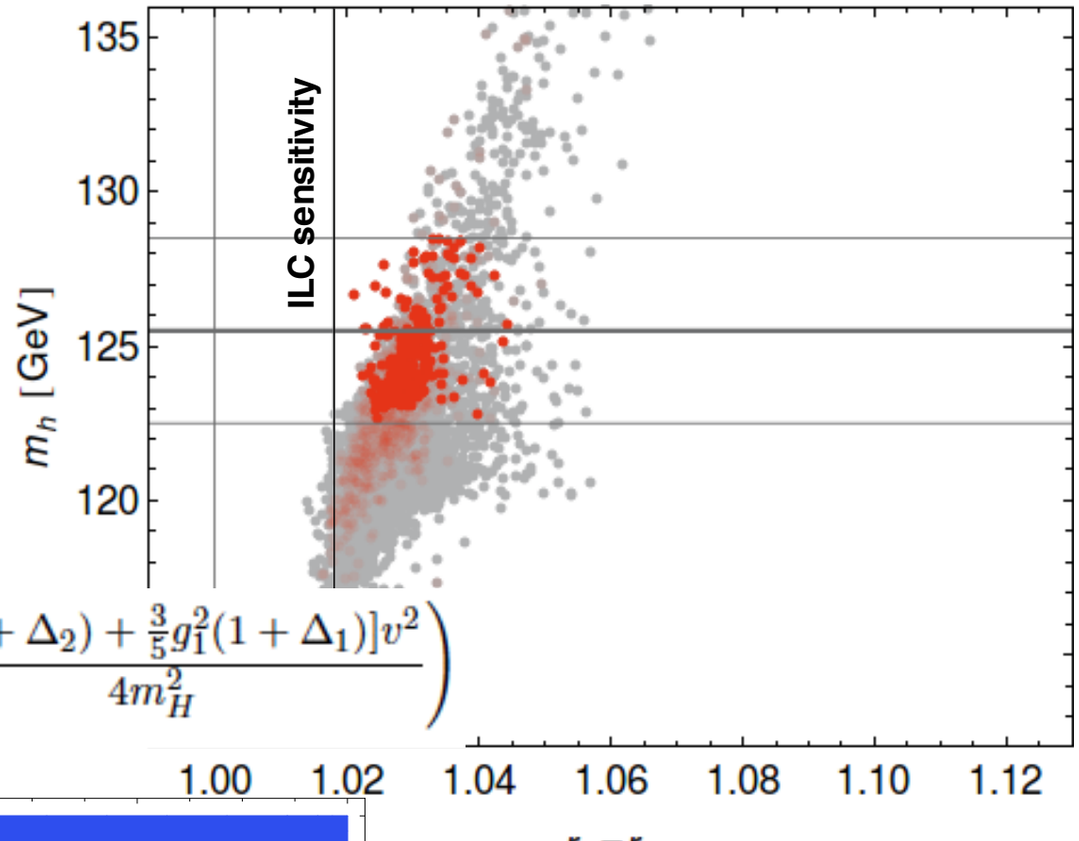




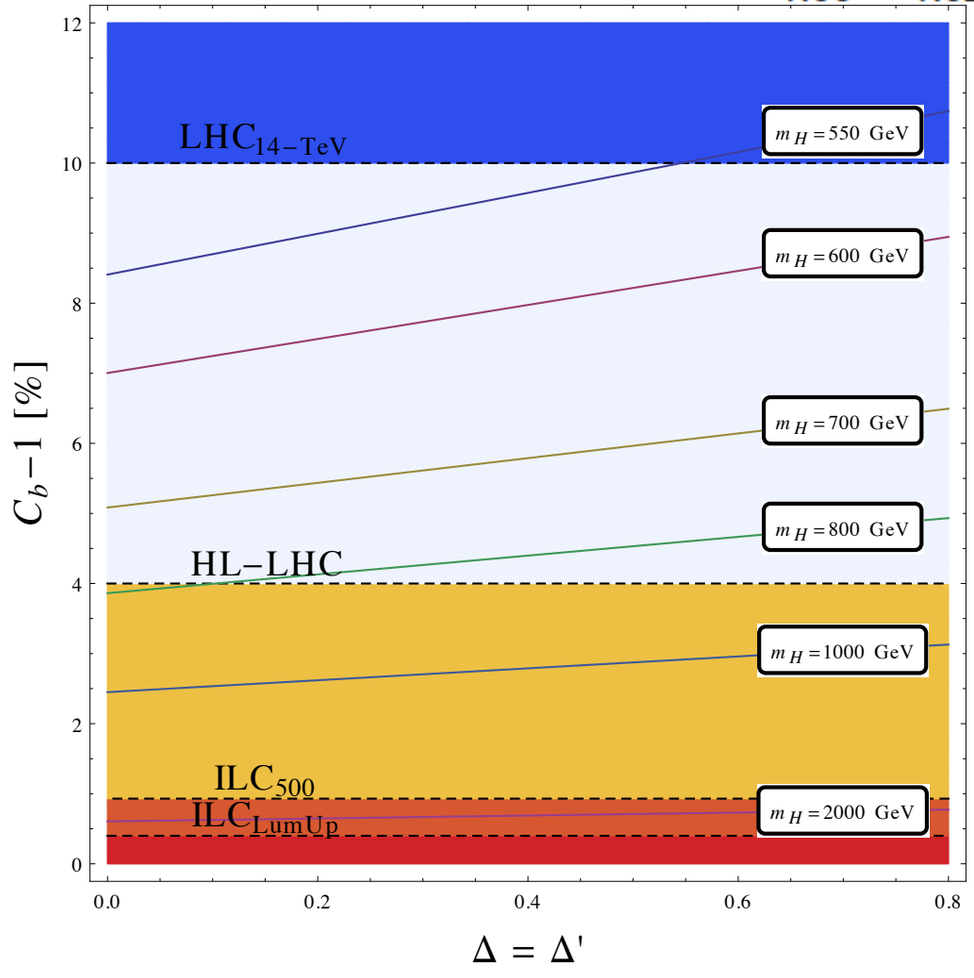
Testable at ILC!



$$c_b^{\text{vector}} \simeq \left(1 - \frac{m_h^2}{m_H^2}\right)^{-1} \left(1 + \frac{[g_2^2(1+\Delta_2) + \frac{3}{5}g_1^2(1+\Delta_1)]v^2}{4m_H^2}\right)$$



$r_b = r_\tau$



$r_b = r_\tau$

Testing D-terms
@ILC
with S.Porto, G. Moortgat-Pick (DESY)

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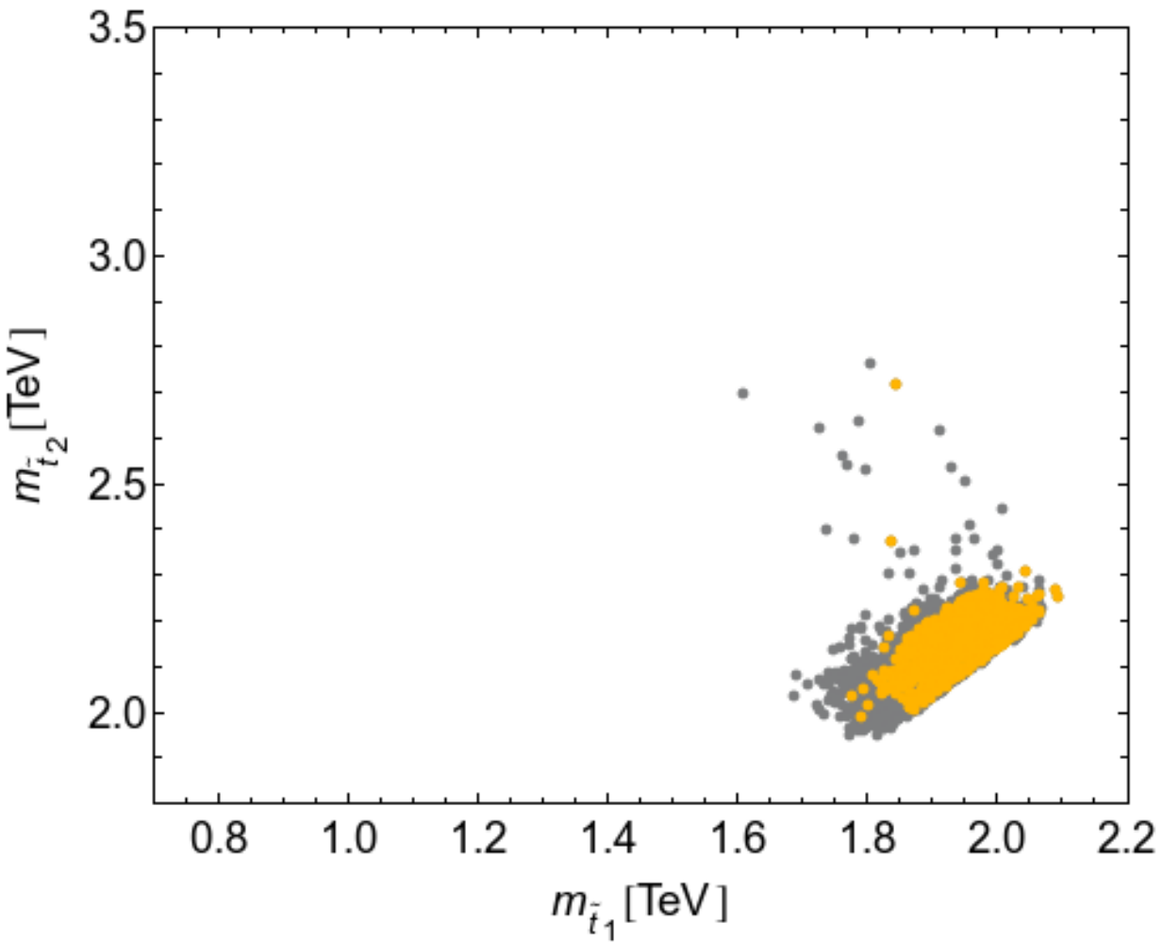
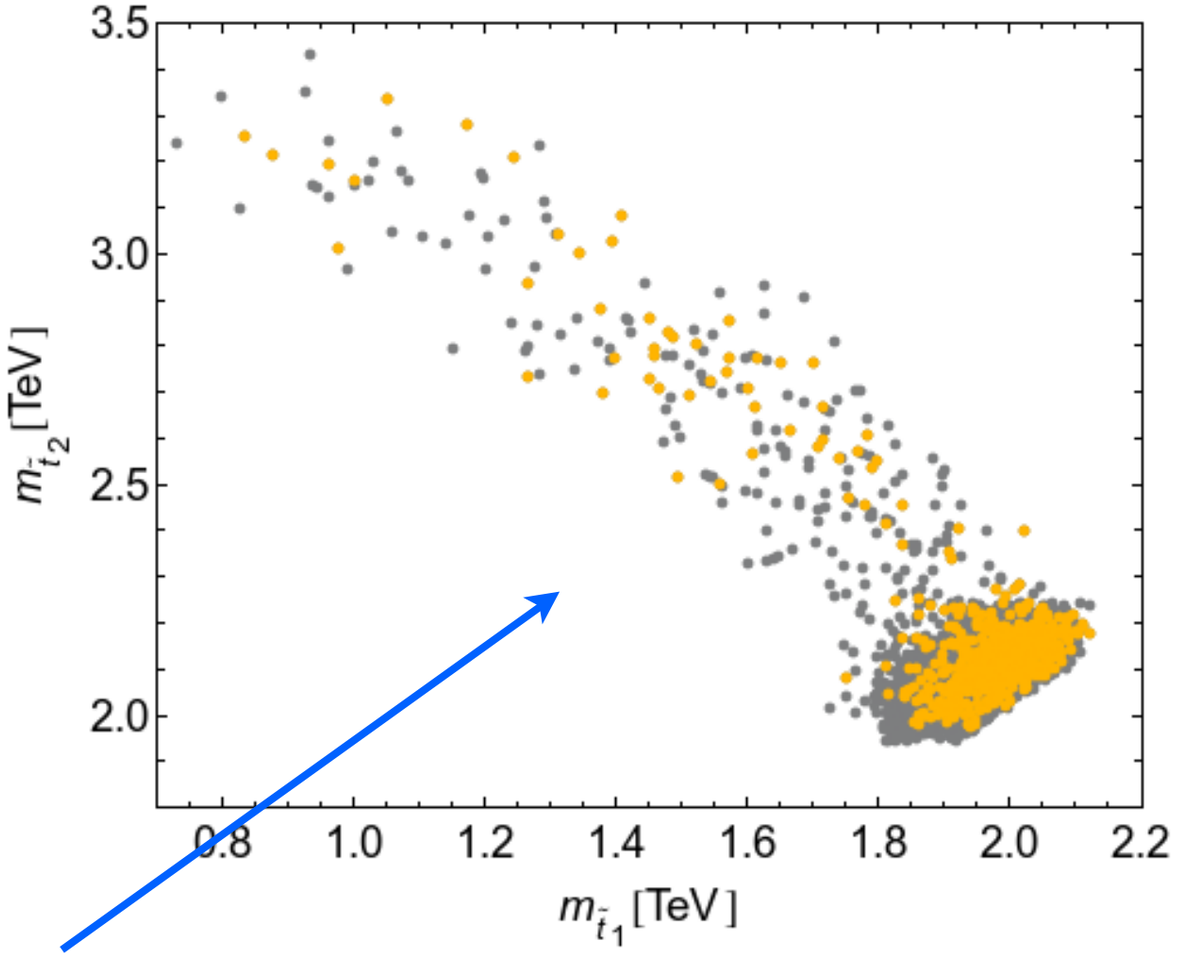
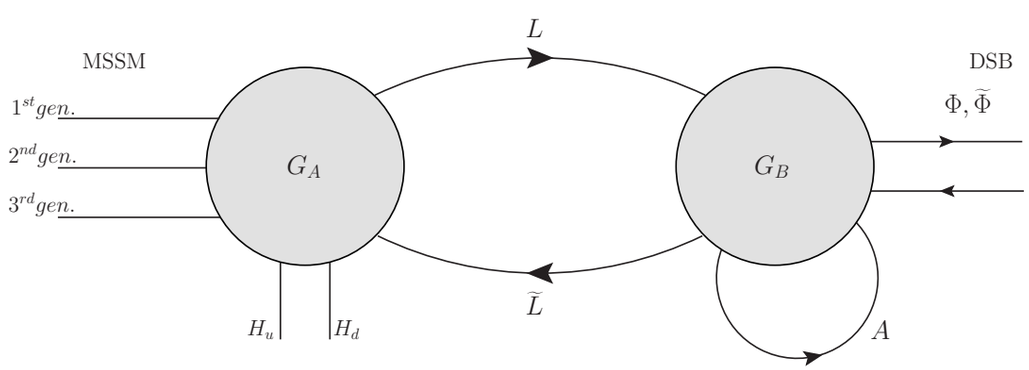
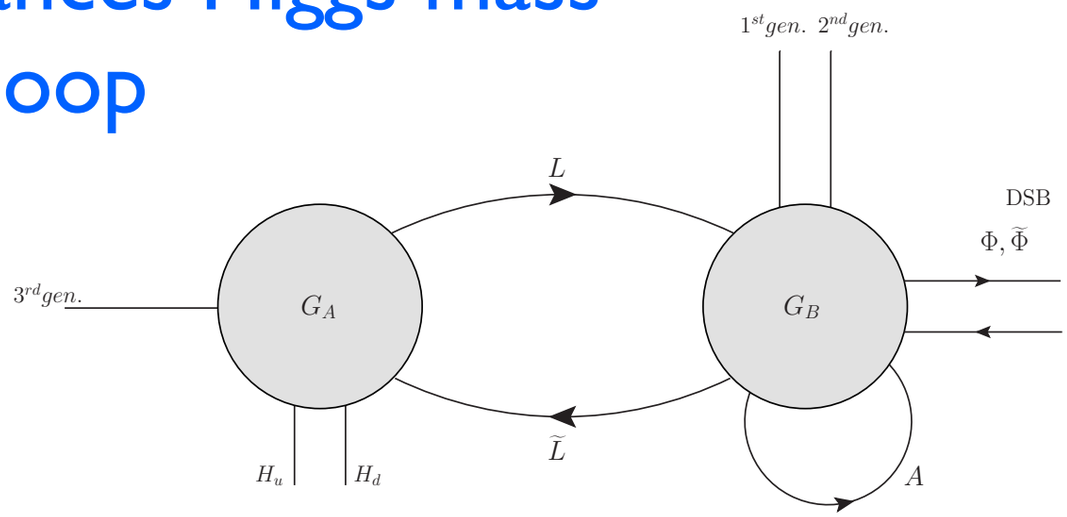
$$m_h^2 \simeq m_z^2 \cos^2(2\beta) + \frac{3}{(4\pi)^2}\frac{m_t^4}{v_{ew}^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}(1-\frac{X_t^2}{12m_{\tilde{t}}^2})\right] + \Delta m_{h,1}^2 = \frac{3m_Z^2}{16\pi^2 v_{ew}^2}(1-\frac{8}{3}\sin\theta_W^2)\cos 2\beta\, m_t^2 \ln\left(\frac{m_{\tilde{q}_L^3}^2}{m_{\tilde{u}_R^3}}\right)$$





Stop splitting enhances Higgs mass @ 1-loop





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	MI	MIIa	MIIb
Input values			
M	233 TeV	288 TeV	260 TeV
$\Lambda_{1,2}$	44.9 TeV	85.6 TeV	111 TeV
Λ_3	190 TeV	206 TeV	208 TeV
m_L^2	47.3 TeV^2	83.3 TeV^2	86.2 TeV^2
v	26.2 TeV	26.5 TeV	25.4 TeV
θ_1, θ_2	1.18, 1.13	1.09,1.33	1.05,1.04
$\tan\beta$	16	12	28
Squark sector			
$m_{\tilde{t}_1}$	1.84 TeV	1.99 TeV	409 GeV
$m_{\tilde{t}_2}$	1.98 TeV	2.06 TeV	3.49 TeV
A_t	-442 GeV	-146 GeV	-141 GeV
$m_{\tilde{b}_R}$	1.95 TeV	2.05 TeV	2.56 TeV
$m_{\tilde{q}_{12,L}}$	2.05 TeV	2.12 TeV	2.19 TeV
$m_{\tilde{q}_{12,R}}$	1.97 TeV	2.10 TeV	2.14 TeV
Slepton sector			
$m_{\tilde{l}_{12,L}}$	738 GeV	314 GeV	515 GeV
$m_{\tilde{l}_{3,L}}$	736 GeV	315 GeV	440 GeV
$m_{\tilde{l}_{12,R}}$	901 GeV	183 GeV	262 GeV
$m_{\tilde{l}_{3,R}}$	899 GeV	110 GeV	4.31 TeV
Gaugino sector			
$m_{\tilde{\chi}_1^0}$	53.2 GeV	116 GeV	154 GeV
$m_{\tilde{\chi}_2^0}$	99.3 GeV	242 GeV	306 GeV
$m_{\tilde{\chi}_3^0}$	187 GeV	750 GeV	818 GeV
$m_{\tilde{\chi}_4^0}$	222 GeV	755 GeV	823 GeV
$m_{\tilde{\chi}_1^\pm}$	96.8 GeV	242 GeV	306 GeV
$m_{\tilde{\chi}_2^\pm}$	225 GeV	756 GeV	823 GeV
$m_{\tilde{g}}$	1.62 TeV	1.66 TeV	1.75 TeV
Higgs sector			
m_{h_0}	125 GeV	127 GeV	125 GeV
m_{H_0}	720 GeV	792 GeV	885 GeV
m_{A_0}	721 GeV	796 GeV	894 GeV
$m_{H^\pm}$	726 GeV	799 GeV	893 GeV

Extensions:

- 6 gauge groups
- resolve issue of MHu^2 and V
- Other SUSY breaking parameterisations?
- Single regime spectrum generator
- Add the states to PDG etc….

A renormalisable way to model an extra dimension

Ex. KK gluons, gluinos, Z', KK W's

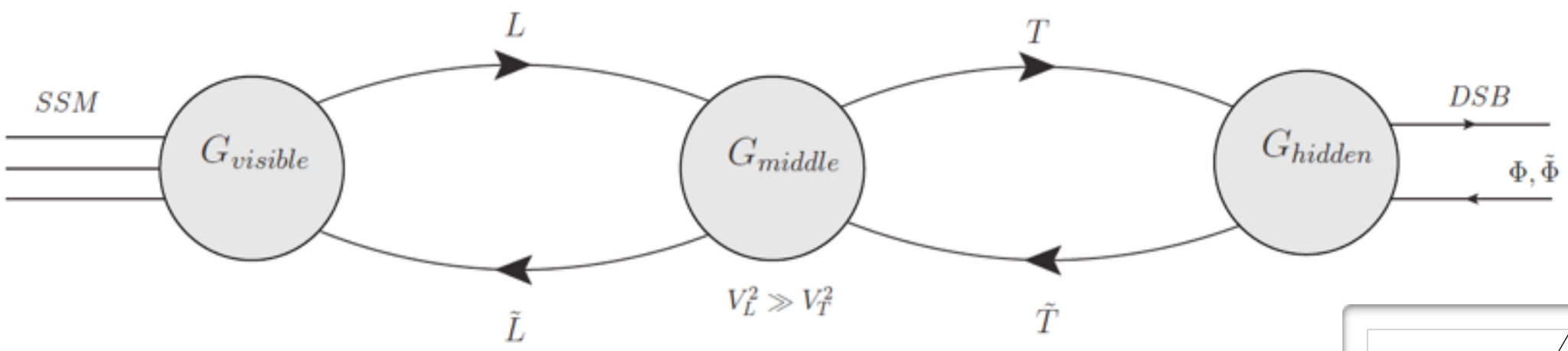
Can talk to FeynArts, Formcalc,CalcHep, Higgsignals, HiggsBounds, WHIZARD,microOMEGA,Vevacious and more

"Deconstructed Holography for Gauge Mediation"

A holographic quiver

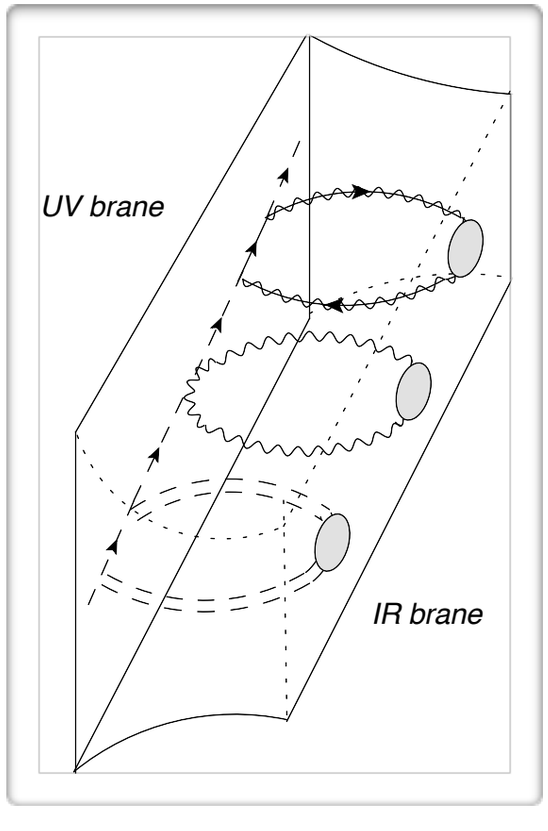
M.M. Rodolfo Russo 1004.3305
M.M. Daniel C. Thompson 1009.4696
M.M. 1210.4935

- non decoupled D-terms
- extra adjoints of SU(2),SU(3)
- Interesting RGE's



4D: operator		Field	Δ	m^2
$\mathcal{O}_{L,R} = \phi^\dagger \phi_{L,R}$	$\rightarrow$	$D(z,x)_{L,R}$	2	-4
$\mathcal{O}^\alpha(x)_{L,R} = -i\sqrt{2}\phi^\dagger q^\alpha_{L,R}$	$\rightarrow$	$\lambda^\alpha(z,x)_{L,R}$	5/2	1/2
$\mathcal{O}^\mu(x)_{L,R} = \bar{q}\sigma^\mu q_{L,R} - i\left(\phi^\dagger \partial^\mu \phi - \partial^\mu \phi^\dagger \phi\right)_{L,R}$	$\rightarrow$	$A^\mu(z,x)_{L,R}$	3	0

Table 1: *Operators corresponding to the bulk fields of the model.*



Thanks for listening!

Moritz McGarrie

Conclusions

- Most models are in bad shape
- Perhaps it is time to panic?
- Natural SUSY is well motivated from bottom up
- Some of these have top-down motivation too
- It does mean sacrificing minimality!