Vrije Universiteit Brussel

Natural SUSY and the 125.5 GeV Higgs

Moritz McGarrie

The MSSM

3-generations:
stops are typically the lightest coloured superpartners

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\tilde{u}_L \;\; \tilde{d}_L)$	$(u_L \;\; d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
($\times 3$ families)	$\bar{u}$	$\tilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\tilde{\nu} \;\; \tilde{e}_L)$	$(\nu \;\; e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
($\times 3$ families)	$\bar{e}$	$\tilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H^+_u \;\; H^0_u)$	$(\tilde{H}^+_u \;\; \tilde{H}^0_u)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H^0_d \;\; H^-_d)$	$(\tilde{H}^0_d \;\; \tilde{H}^-_d)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

Table 1.1: Chiral supermultiplets in the Minimal Supersymmetric Standard Model. The spin-0 fields are complex scalars, and the spin-1/2 fields are left-handed two-component Weyl fermions.

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^\pm \;\; \widetilde{W}^0$	$W^\pm \;\; W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Table 1.2: Gauge supermultiplets in the Minimal Supersymmetric Standard Model.

Ref: A supersymmetry primer Arxiv:9709356v6

1.The Higgs mass 125.5 GeV

The MSSM at one-loop

average stop mass

top 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 +....

MSSM fine tuning: little hierarchy problem

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

Light Higgsino

For a natural cancellation these should be of the same order

Light stops

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

Light(ish) Gluino

Light wino

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

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)

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

- Dynamical explanation? Soft masses cannot be the same

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

- 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

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

} → ~> 1.5 TeV exclusions (first two rows)

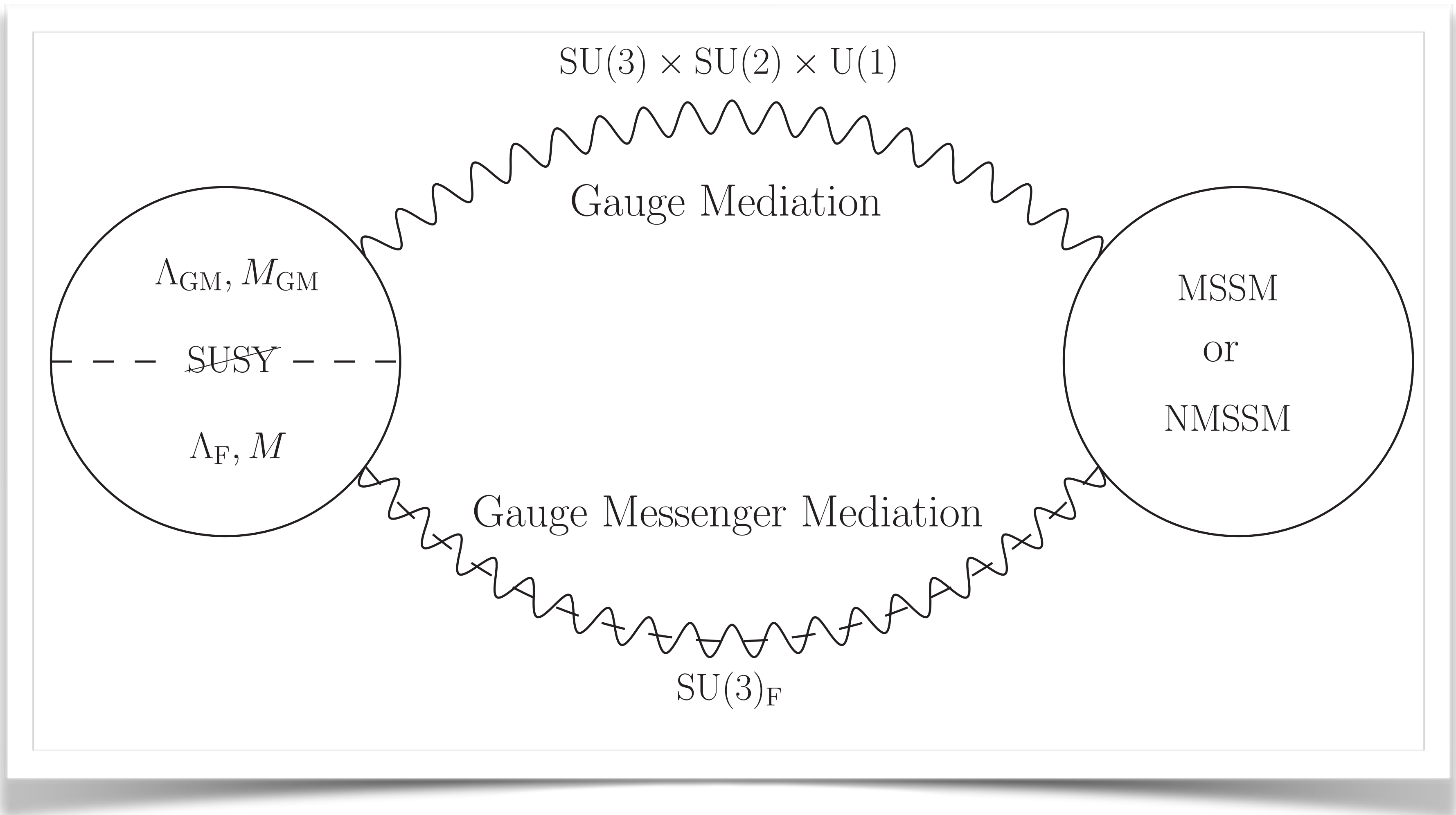
→ ~> 400 GeV exclusions (third row)

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

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

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

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

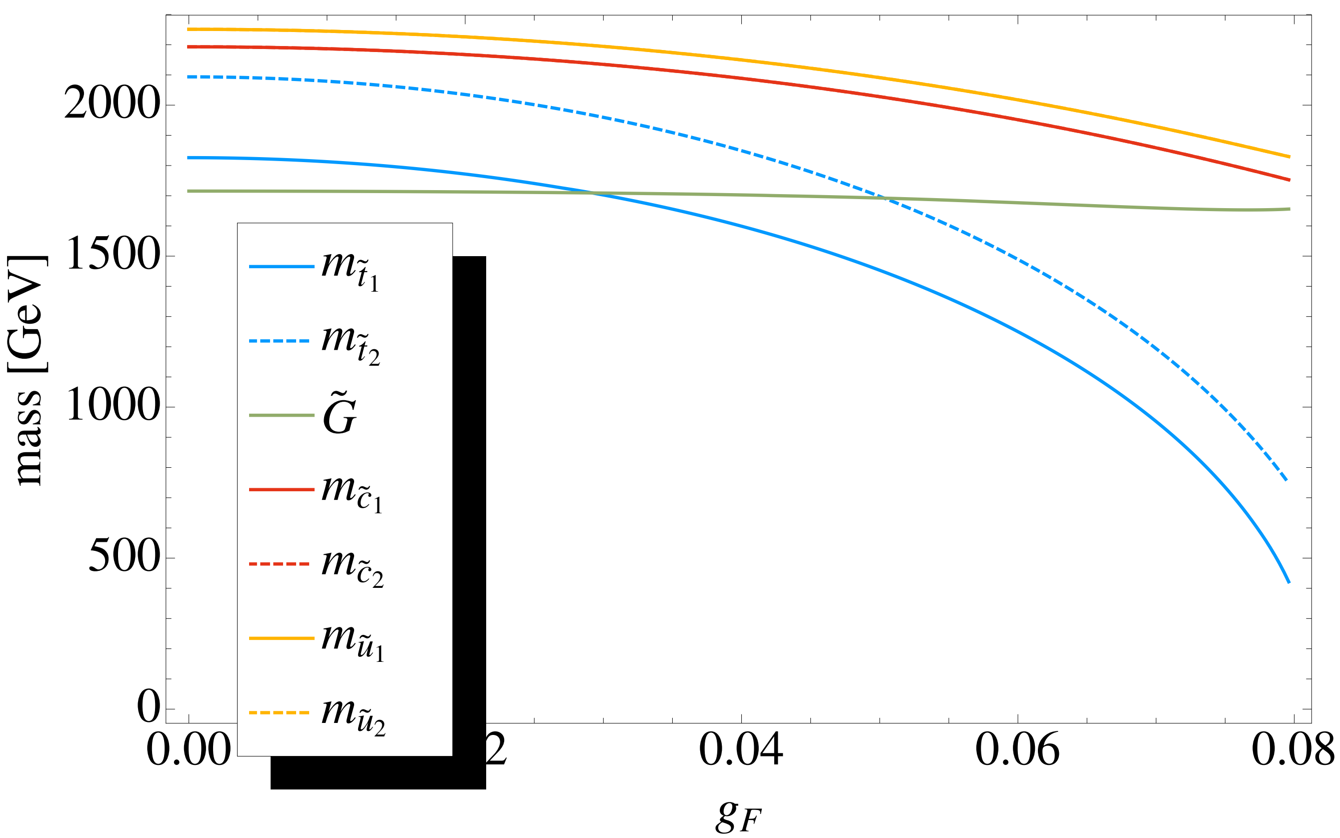
From GMSB

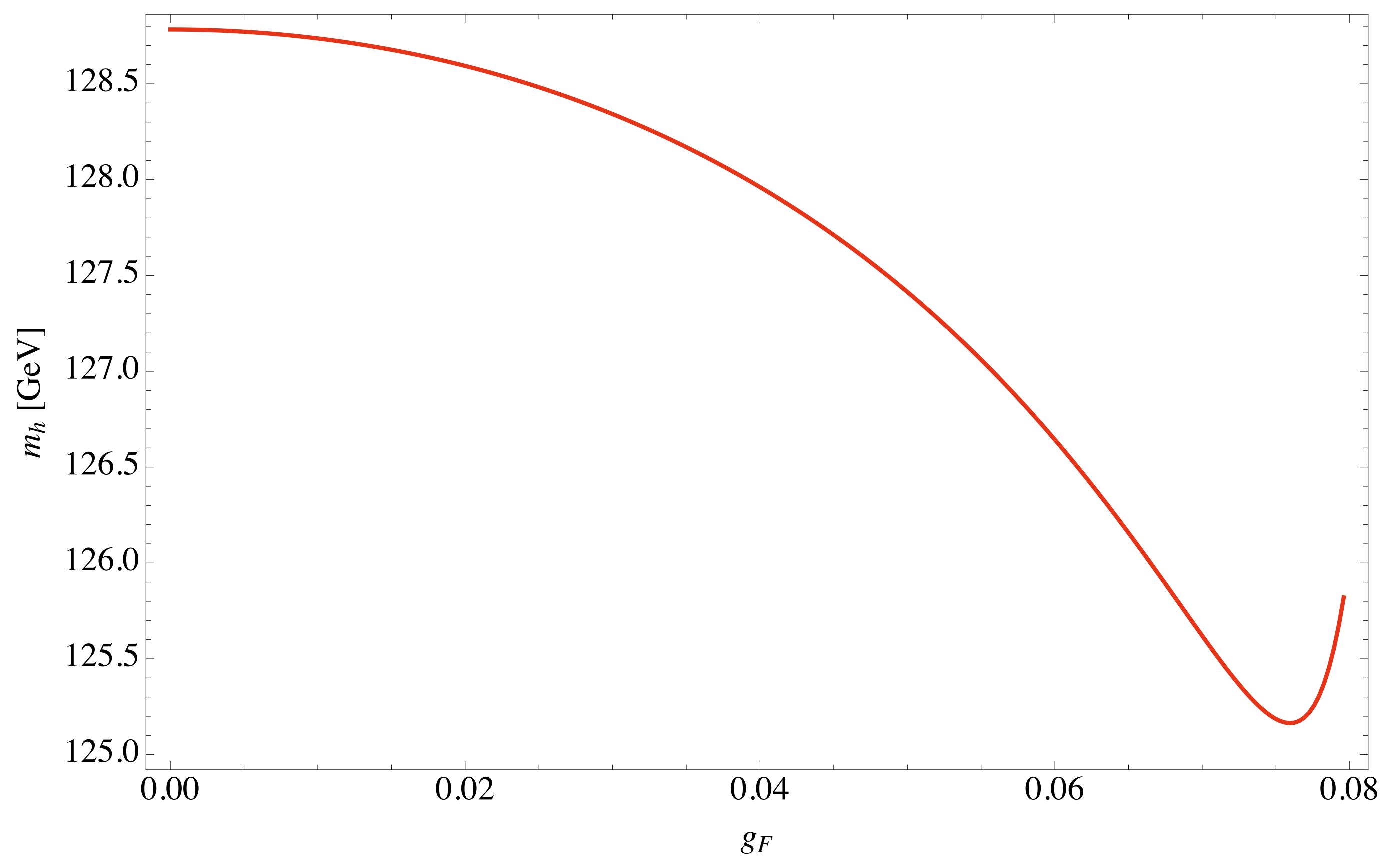
$$m^2_{Q,U,D,\mathrm{GMSB}} \sim +\sum_i \frac{g^4_{SM,i}}{(16\pi^2)^2}\left(\frac{F}{M}\right)^2 \begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$$

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

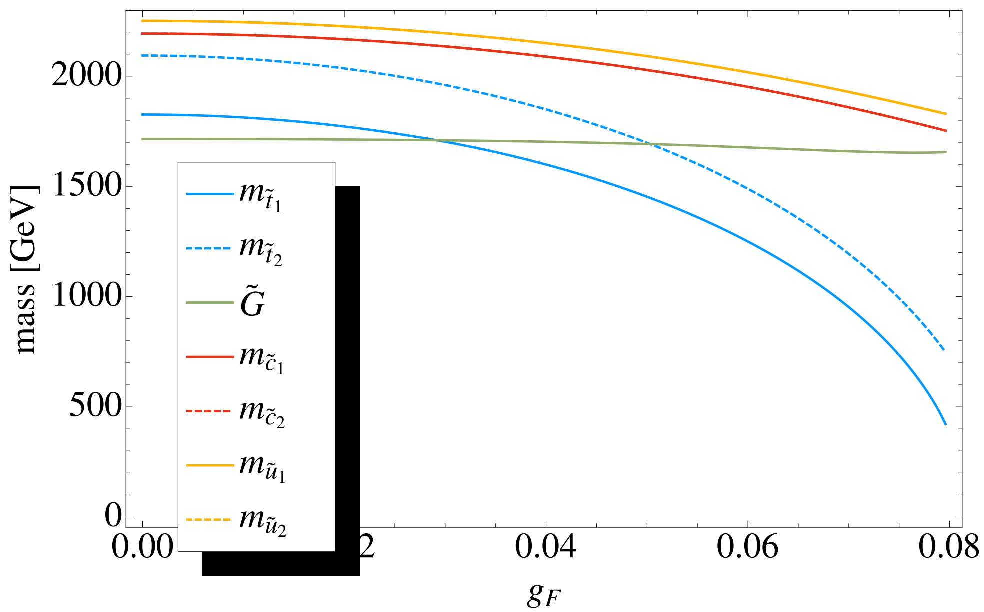
Figure 2. A plot [Left] of the squark and gluino masses for model 1 with the NMSSM. [Right] a plot of Higgs mass versus g_F for the same range. $\lambda = 0.8$, $\kappa = 0.8$, $v_s = 1000$, $m^2_{H_d} = m^2_{H_u} = 10^5$, $\Lambda = \Lambda_F = 2.3 \times 10^5$, $M = 10^7$, $\tan\beta = 1.5$.

Flavour changing neutral currents

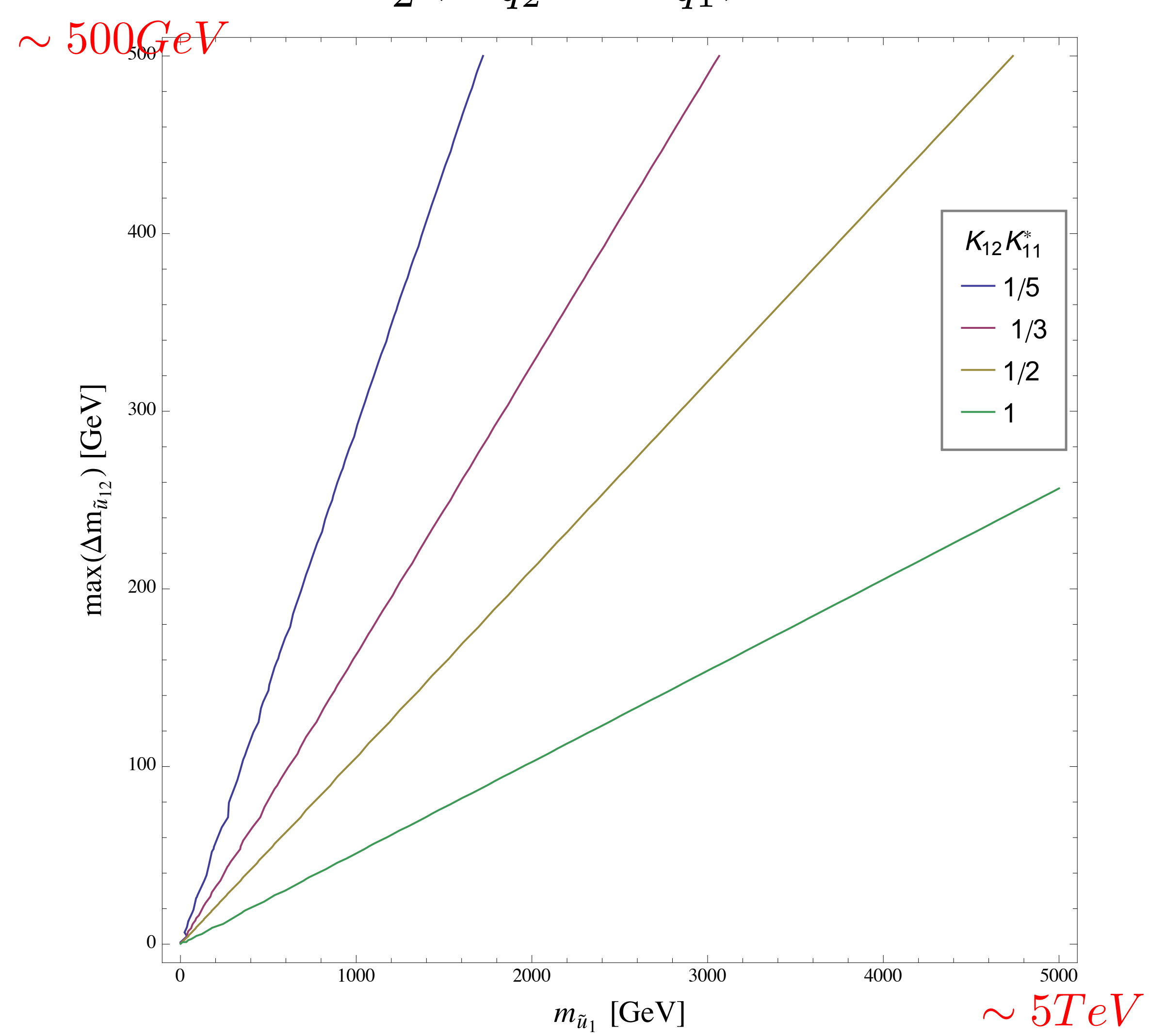
(S.Abel & MM) 1404.1318

$\delta_{u,12} < 0.1$

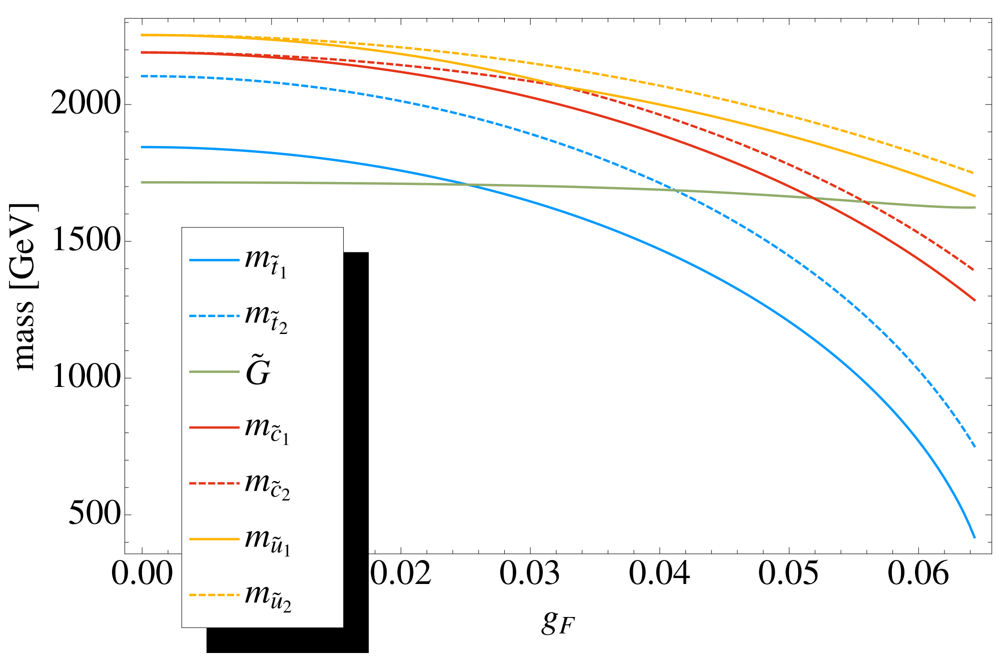
Model 1: degenerate 1st & 2nd



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



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

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

$$(+) + (-) \sim 0$$

↑ 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

(S.Abel & MM) 1404.1318

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

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

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

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

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

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

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

Rank 1

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

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

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

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?

1.The Higgs mass 126 GeV

The MSSM at one-loop

top mass

average stop mass

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

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

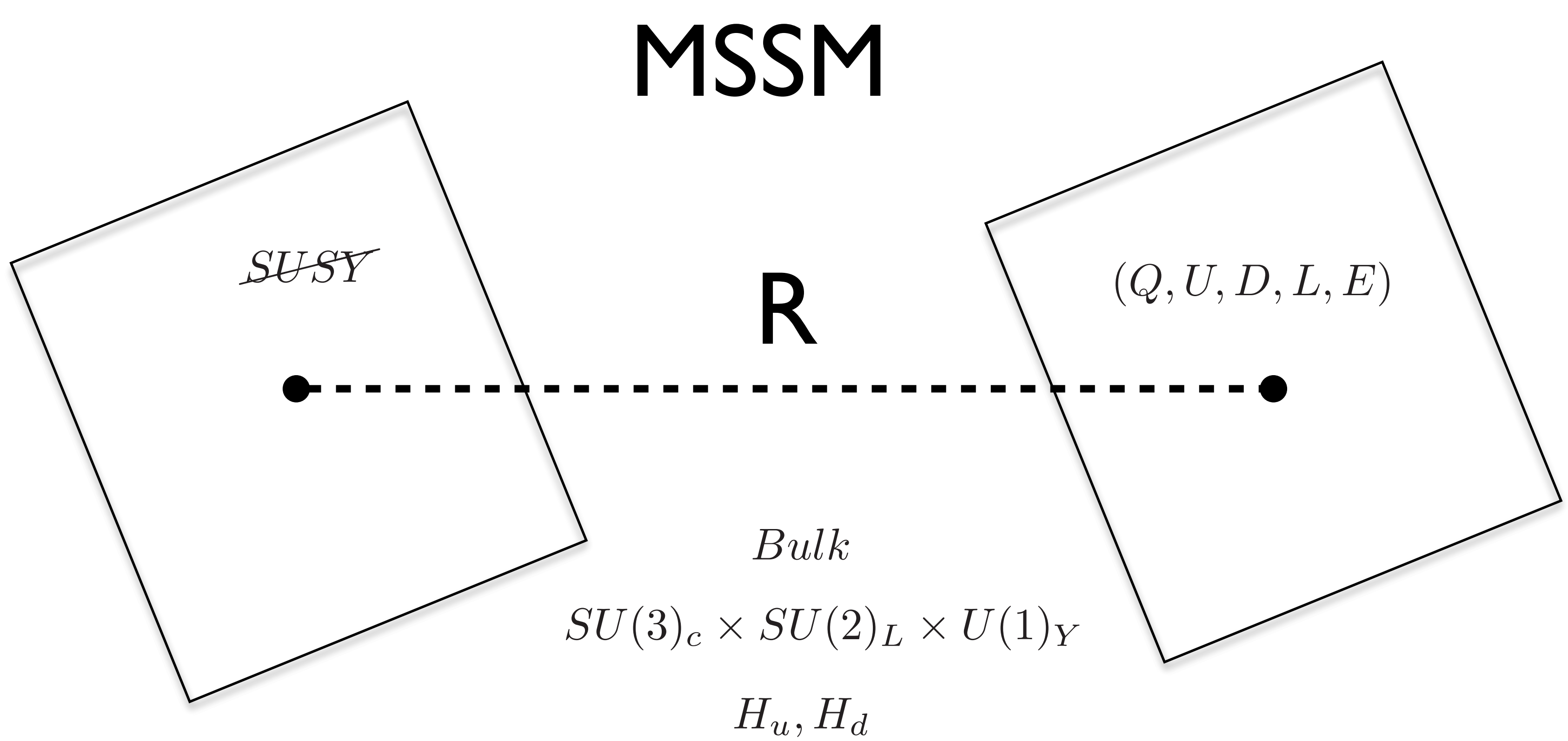
$$X_t = A_t - \mu \cot\beta$$

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 +....

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

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

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 value of At?"

4+d dimensional MSSM

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

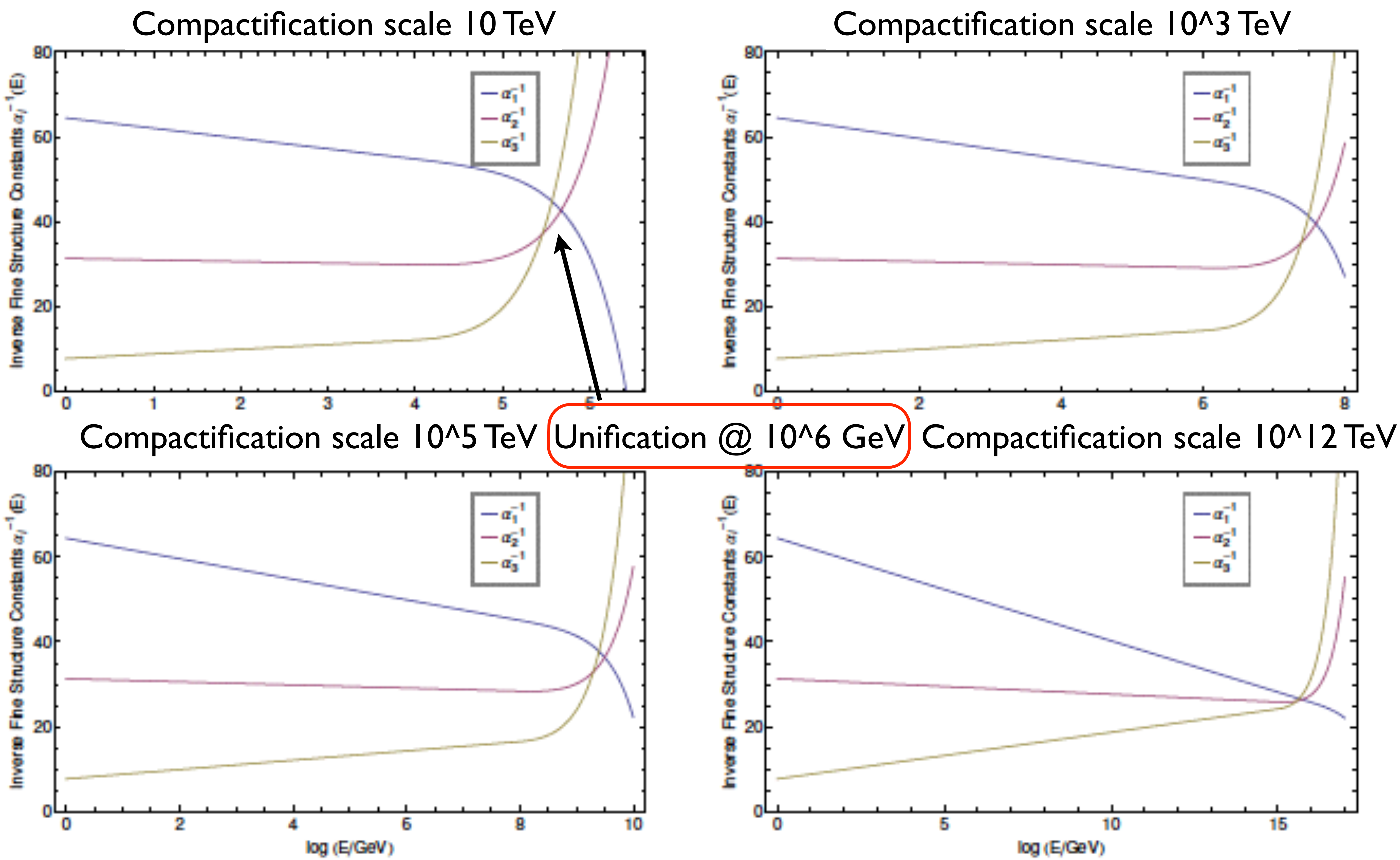


Figure 1. *Running of the inverse fine structure constants $\alpha^{-1}(E)$, for three different values of the compactification scales 10 TeV (top left panel),* 10^3 *TeV (top right),* 10^5 *TeV (bottom left) and* 10^{12} *TeV (bottom right), with M_3 of 1.7 TeV, as a function of log(E/GeV).*

Compactification scale 10 TeV

Compactification scale 10^3 TeV

Large splitting here

small splitting here

Flavour hierarchy just an RGE effect?

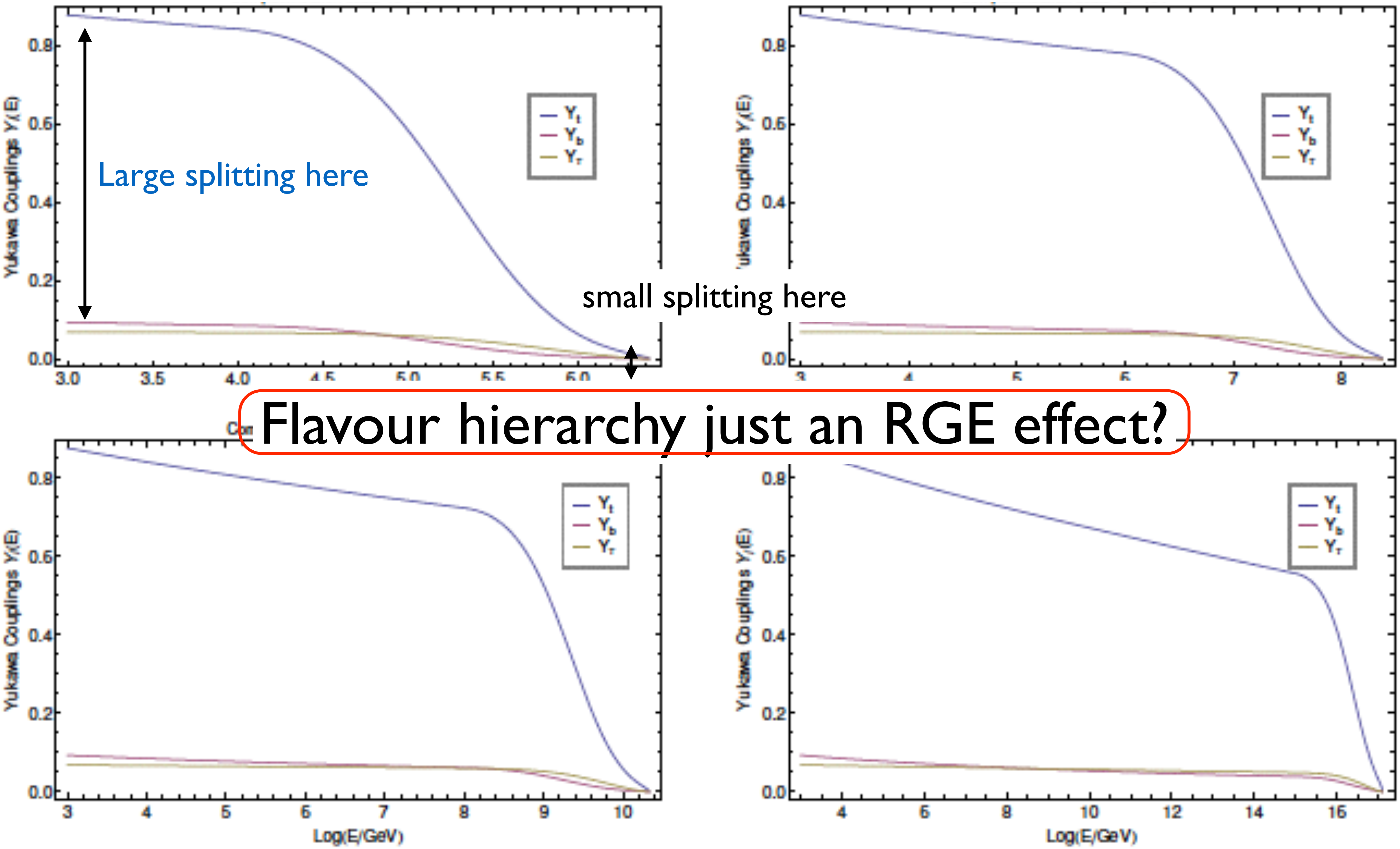


Figure 2. *Running of Yukawa couplings Y_i, for three different values of the compactification scales: 10 TeV (top left panel), 10^3 TeV (top right), 10^5 TeV (bottom left) and 10^{12} TeV (bottom right), with $M_3[10^3]$ of 1.7 TeV, as a function of log(E/GeV).*

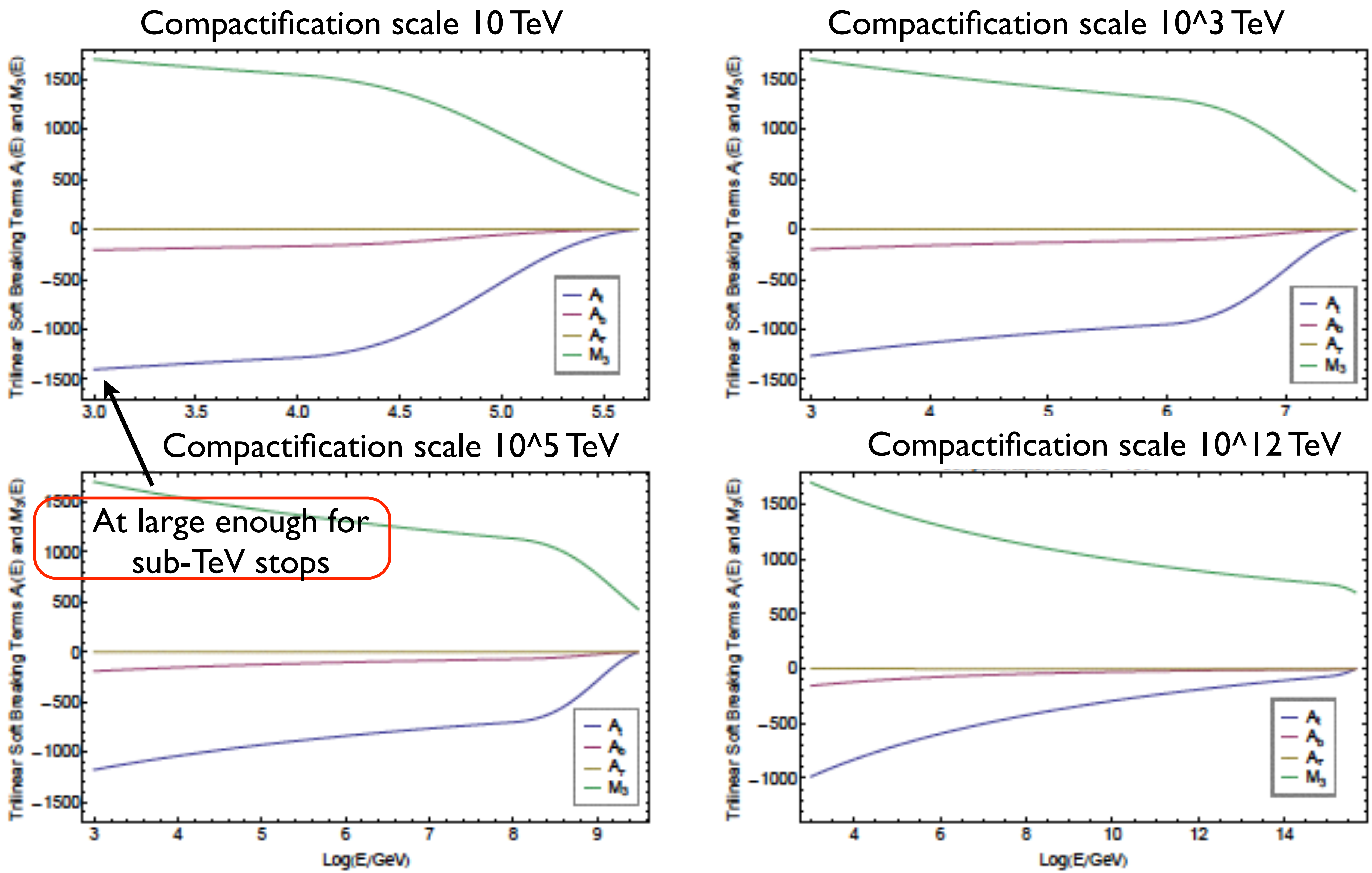
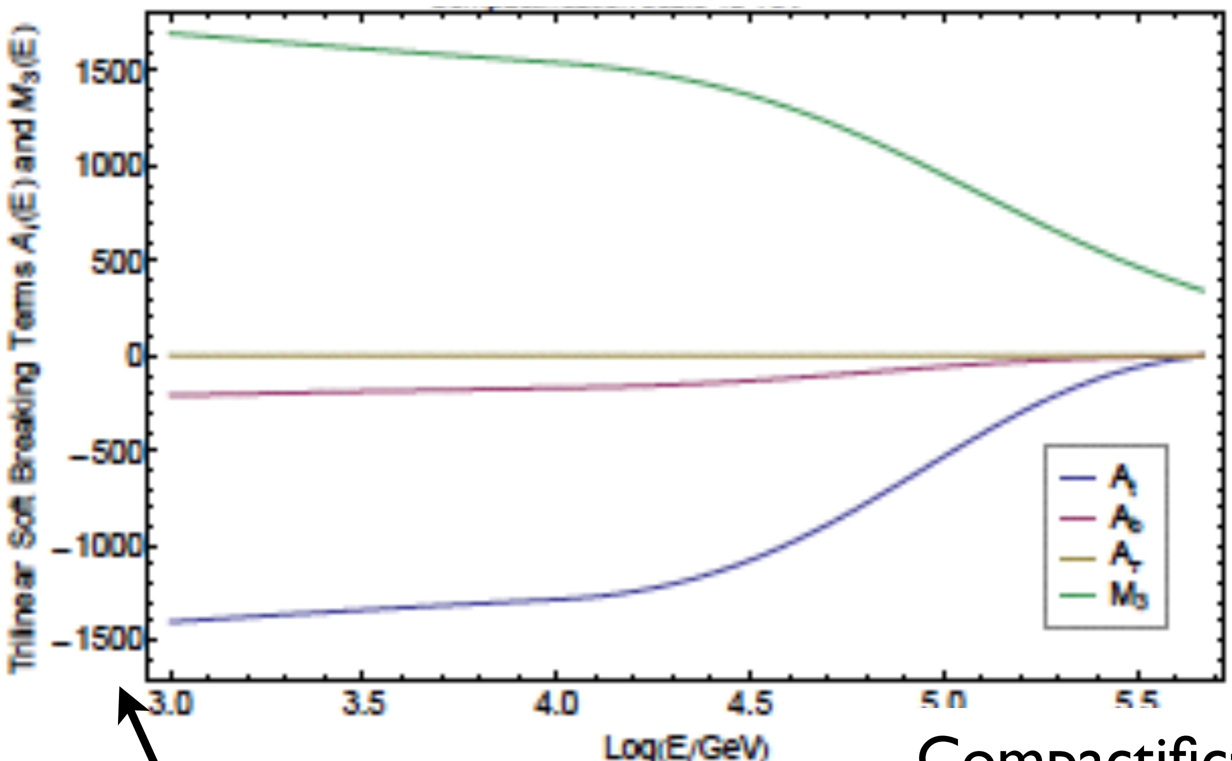
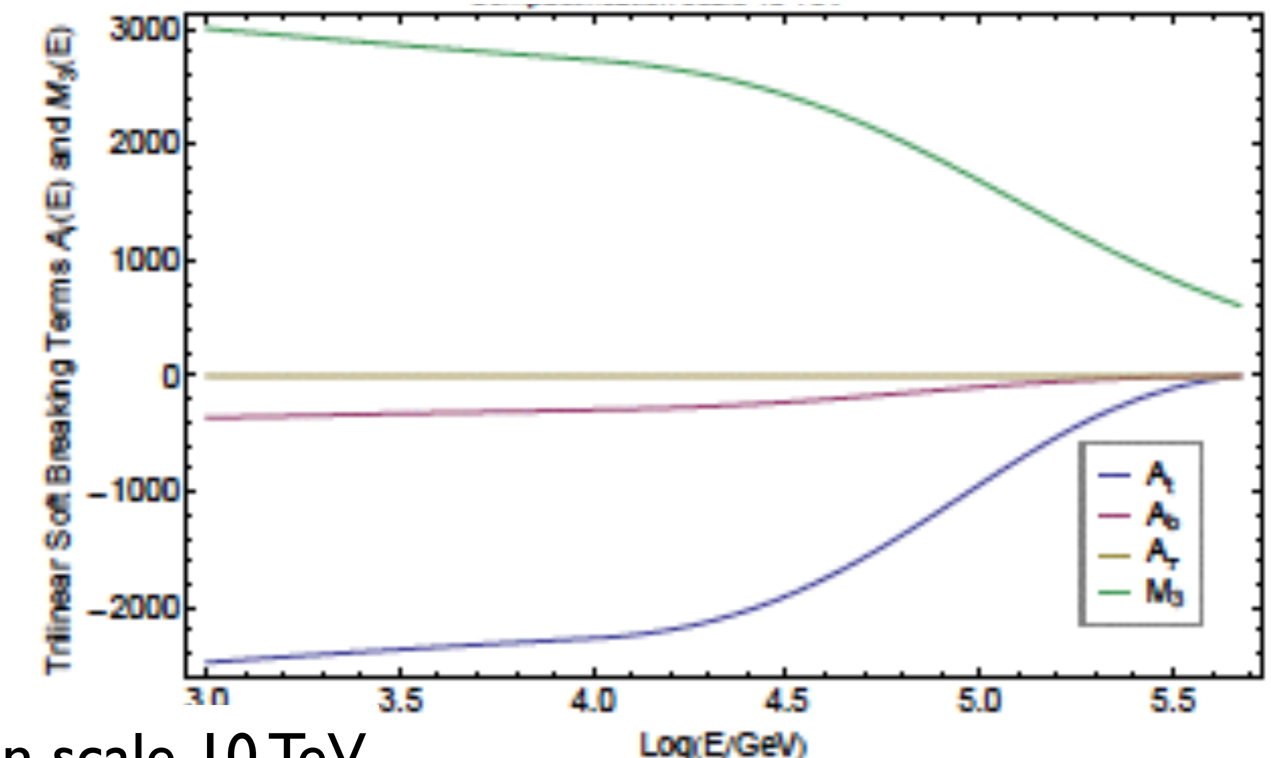


Figure 3. *Running of trilinear soft terms $A_i(3,3)(E)$, for three different values of the compactification scales 10 TeV (top left panel), 10^3 TeV (top right), 10^5 TeV (bottom left) and 10^{12} TeV (bottom right), with $M_3[10^3]$ of 1.7 TeV, as a function of log(E/GeV).*

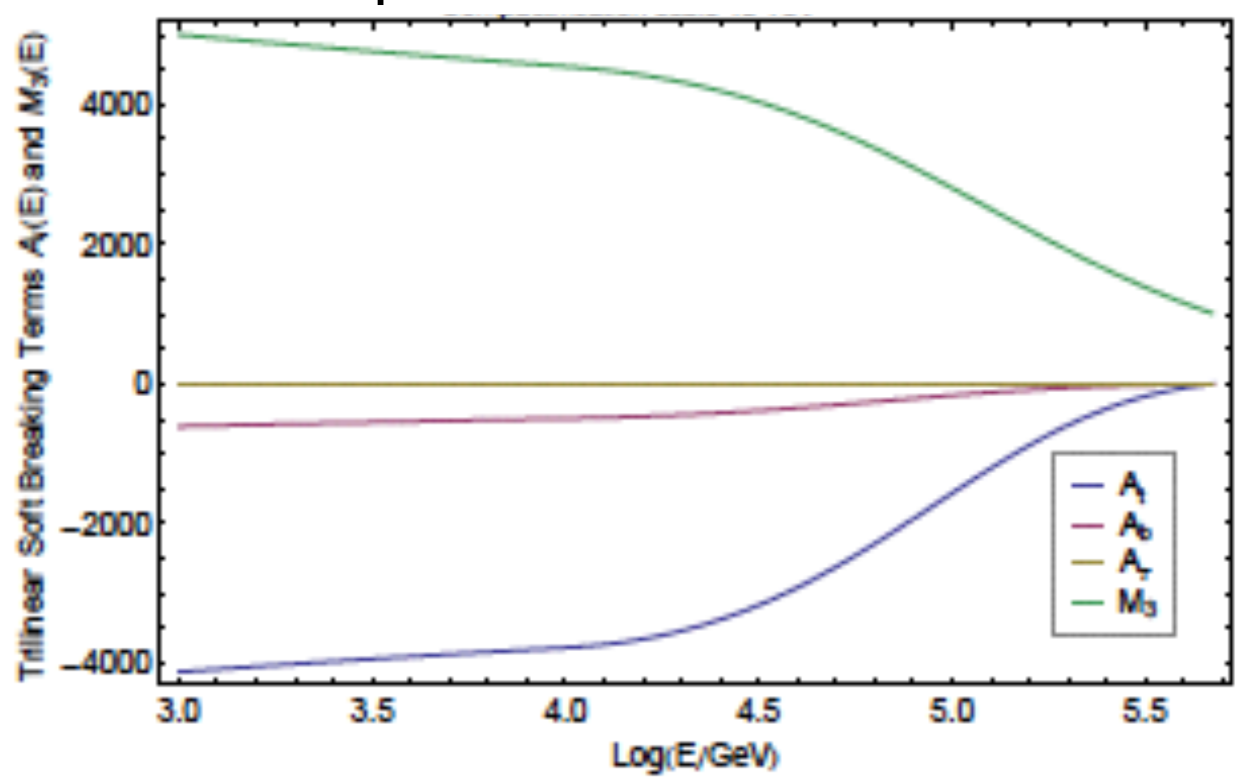
Compactification scale 10 TeV

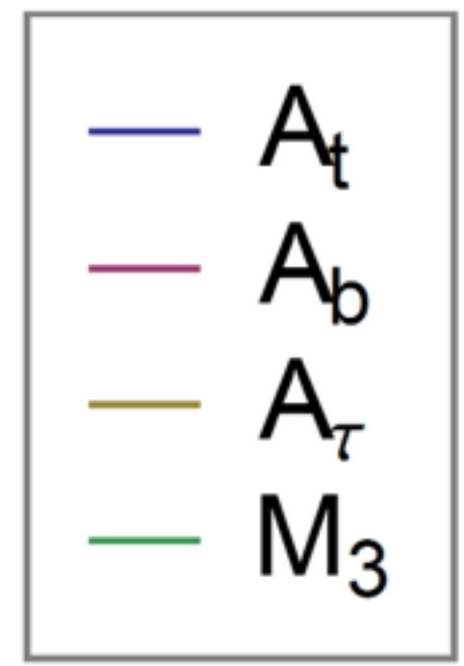


Compactification scale 10 TeV



Compactification scale 10 TeV





At large enough for sub-TeV stops

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!

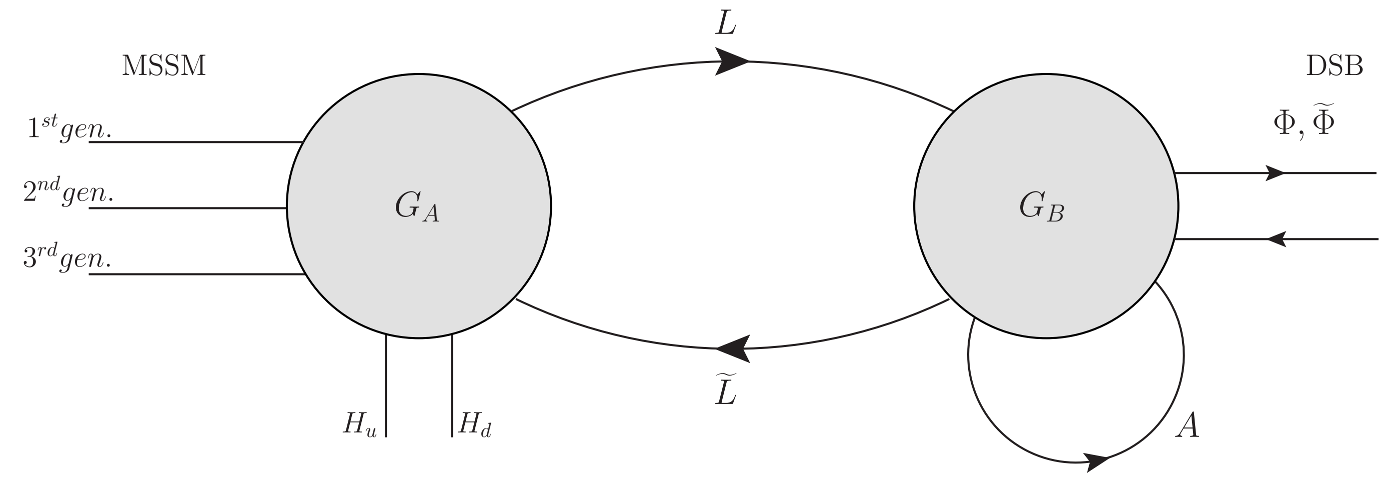
Back up slides

Non decoupled D-terms

(Aoife Bharucha, Andreas Goudelis & MM) 1310.4500

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

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

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

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

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

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

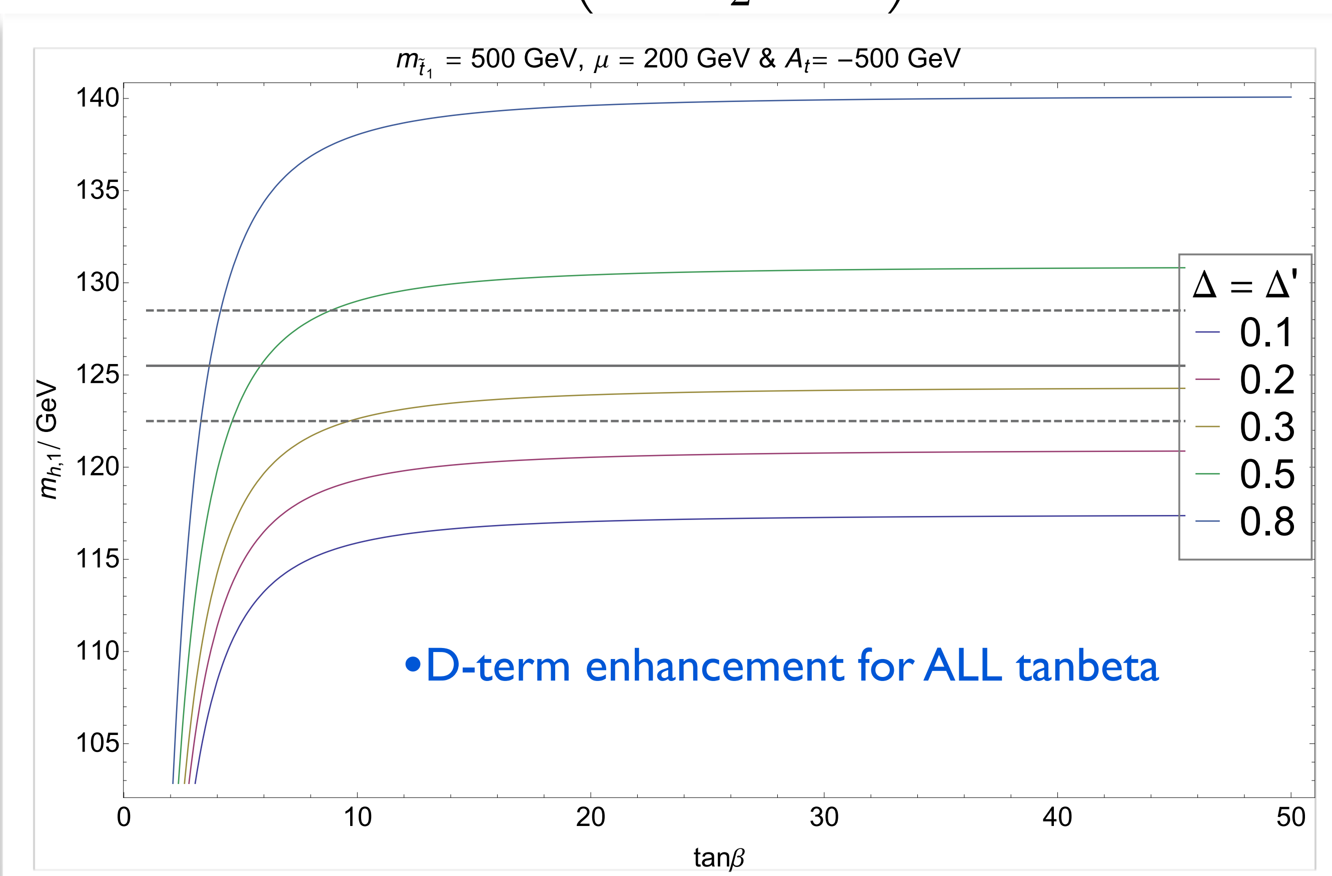
D-terms Vs NMSSM

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

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

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

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



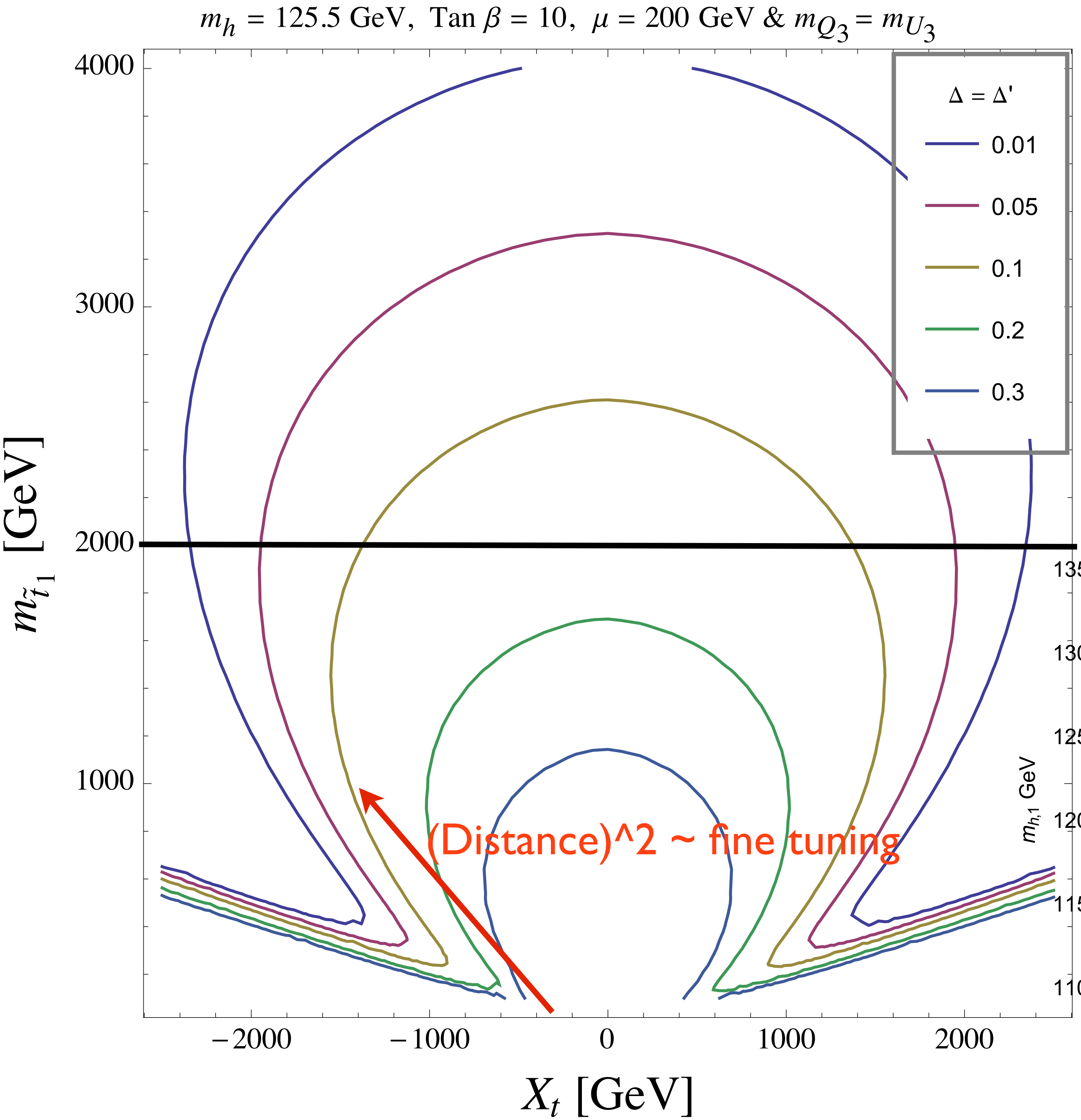
• D-term enhancement for ALL tanbeta

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

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

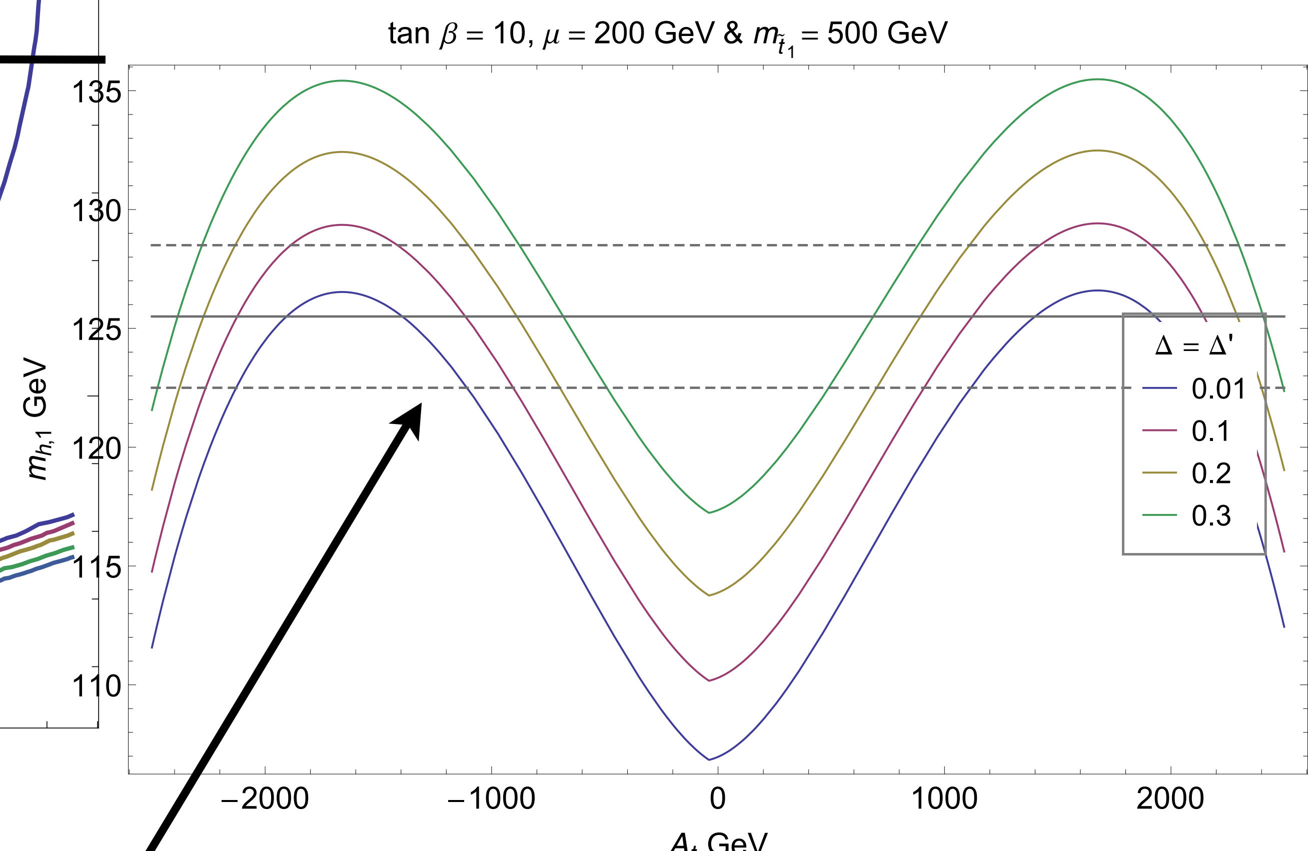
$$m_{h_0}^2 = m_z^2\cos(2\beta) + \lambda^2 v_{ew}^2\sin(2\beta)$$

• 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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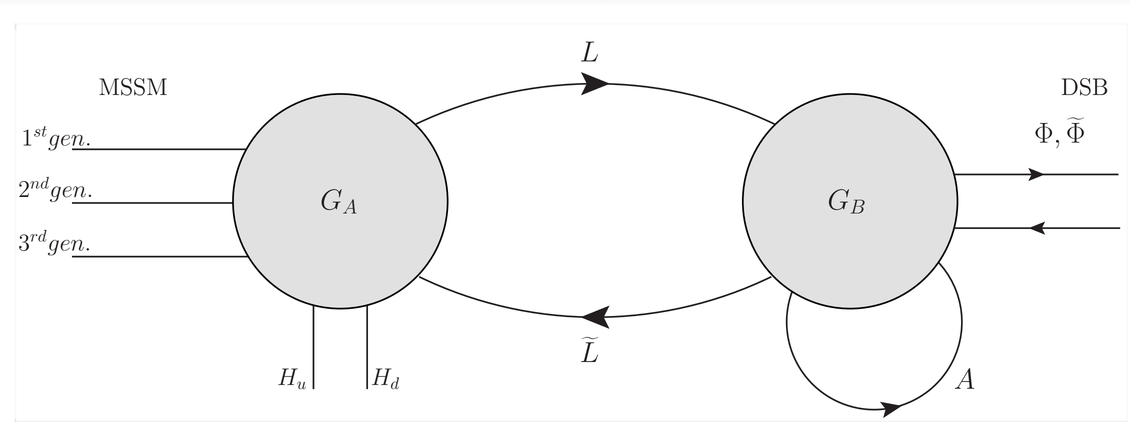
SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)_A, \mathrm{SU}(2)_B, \mathrm{SU}(3)_c, U(1)_B, \mathrm{SU}(2)_A)$	R-Parity
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{1}, \mathbf{3}, 0, \mathbf{2})$	-1
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{1}, \mathbf{1}, 0, \mathbf{2})$	-1
$\hat{H}_d$	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	$(1, \mathbf{1}, \mathbf{1}, 0, \mathbf{1})$	-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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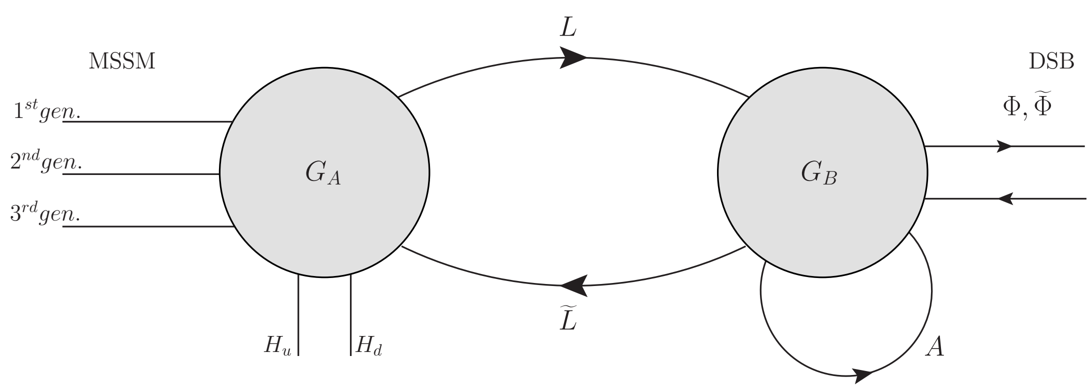
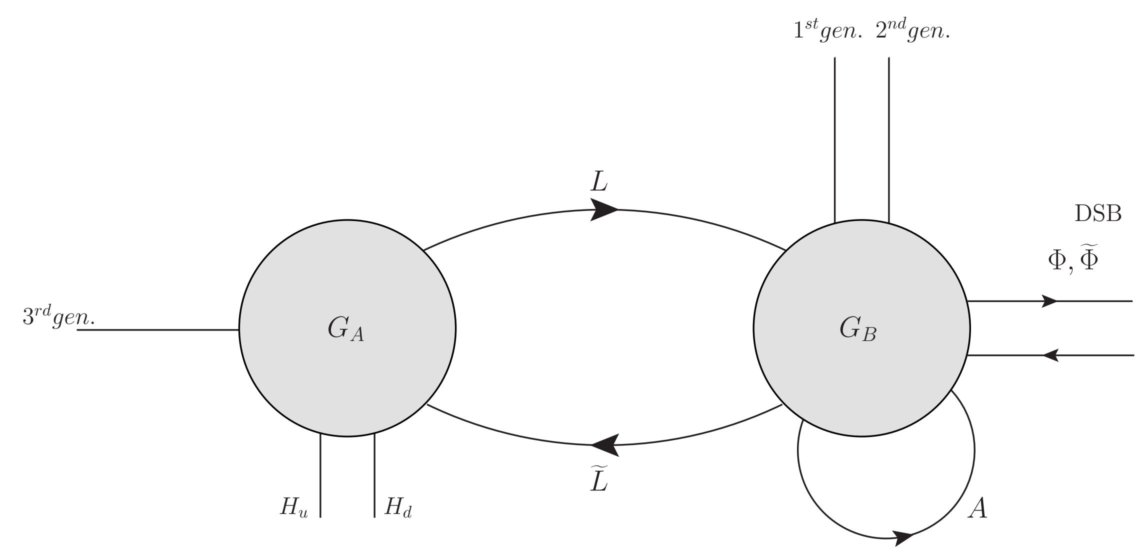
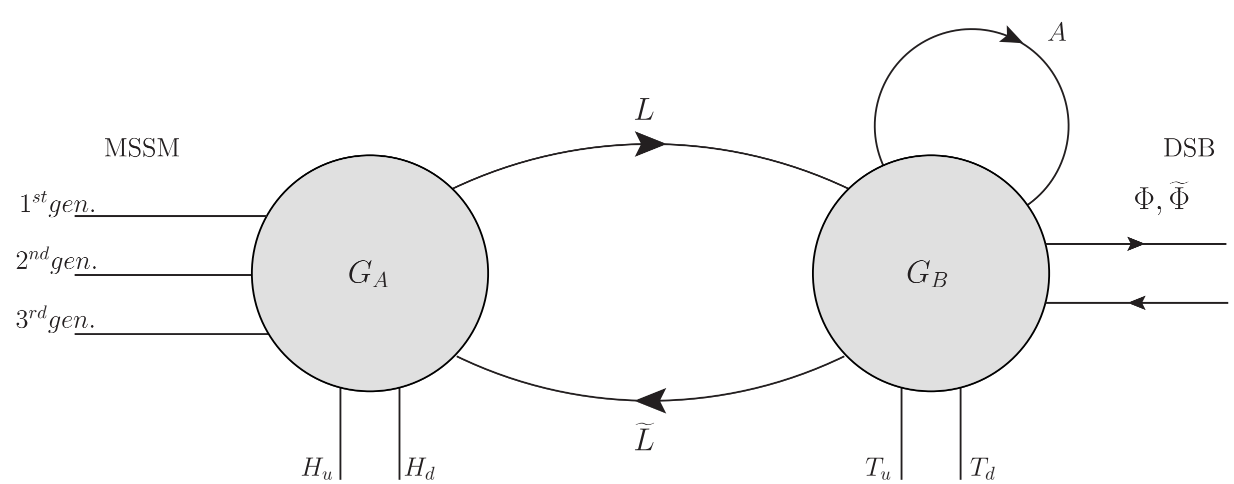
The Quiver Variations





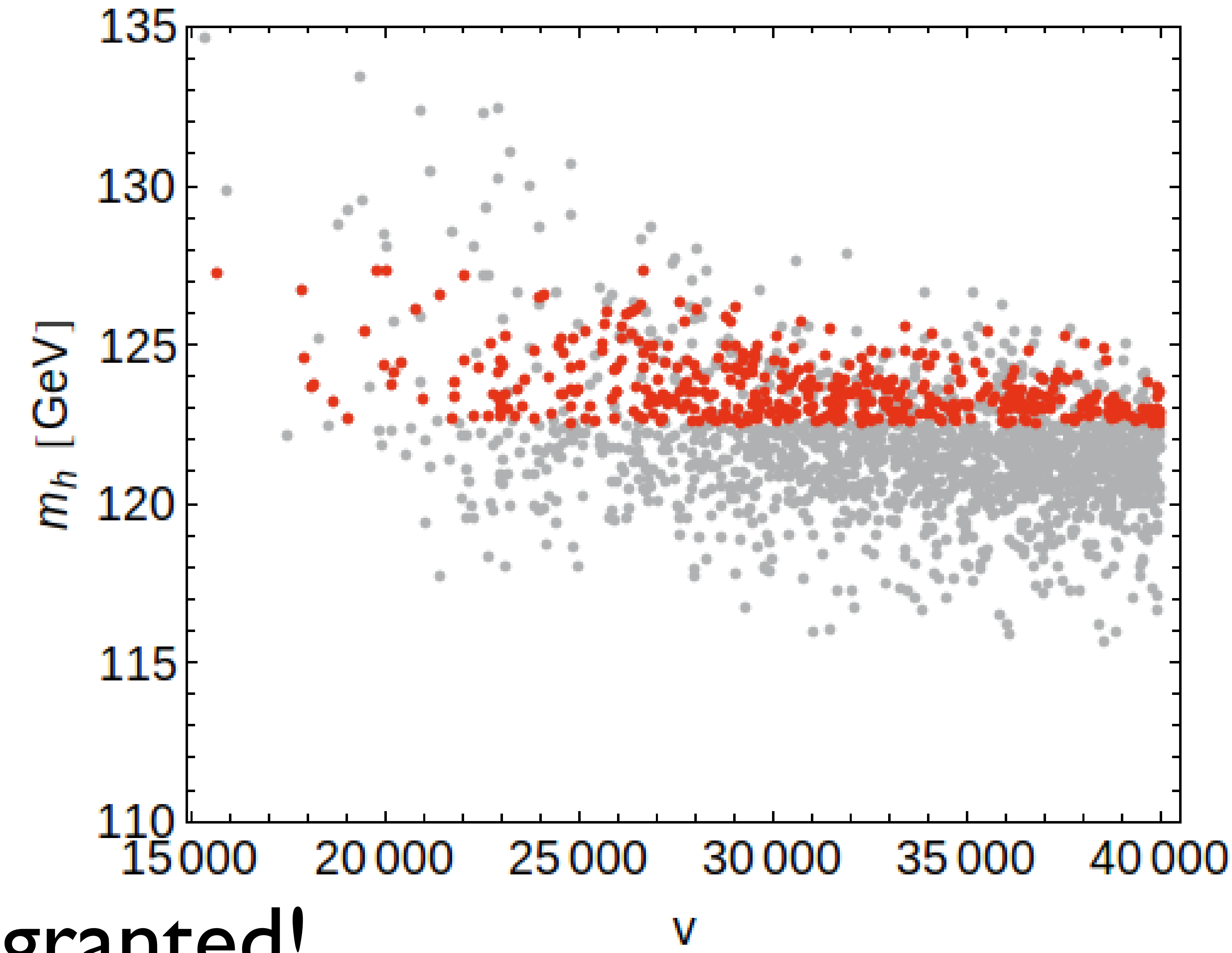


Wish list

- $v < 10\text{TeV}$

  $m_L^2 > m_v^2$

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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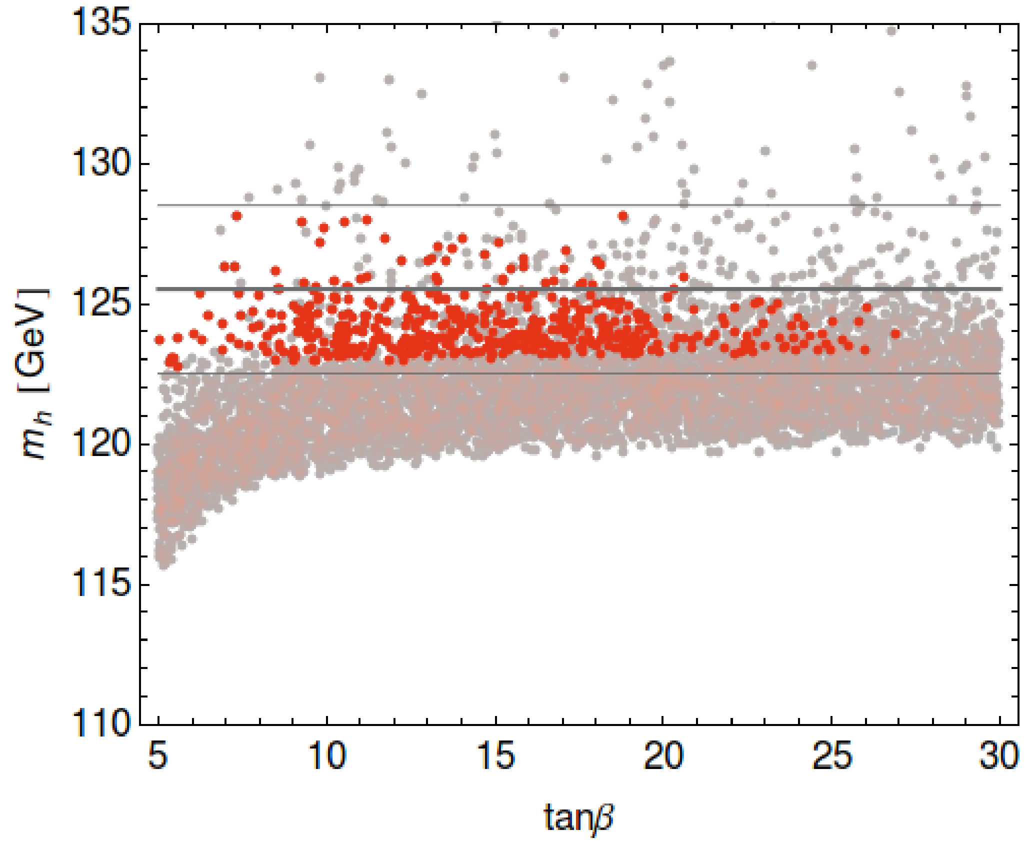

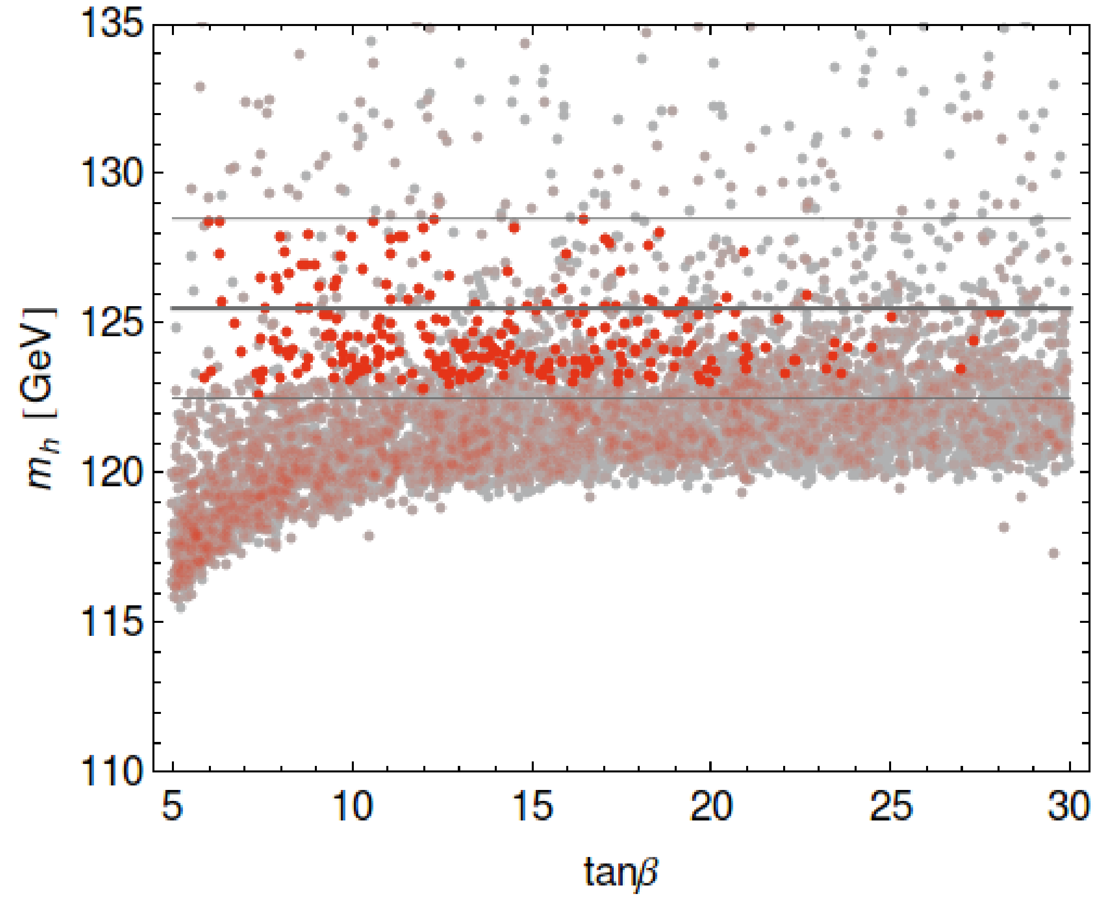

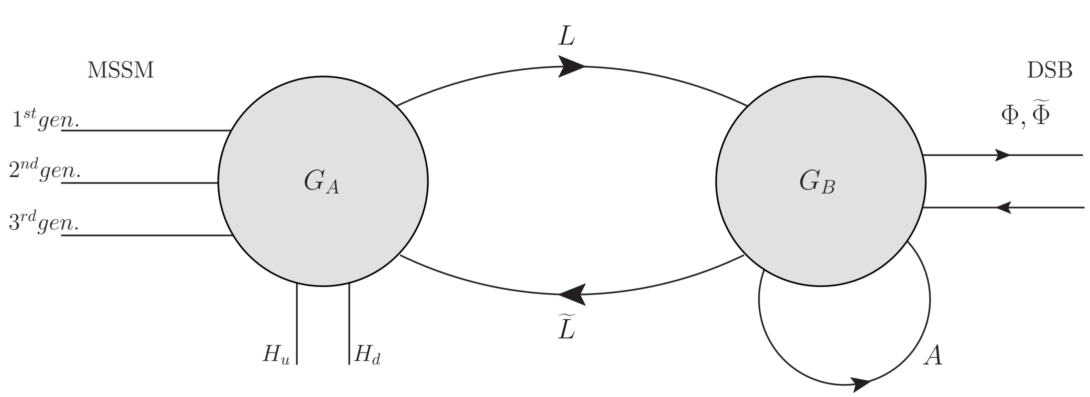

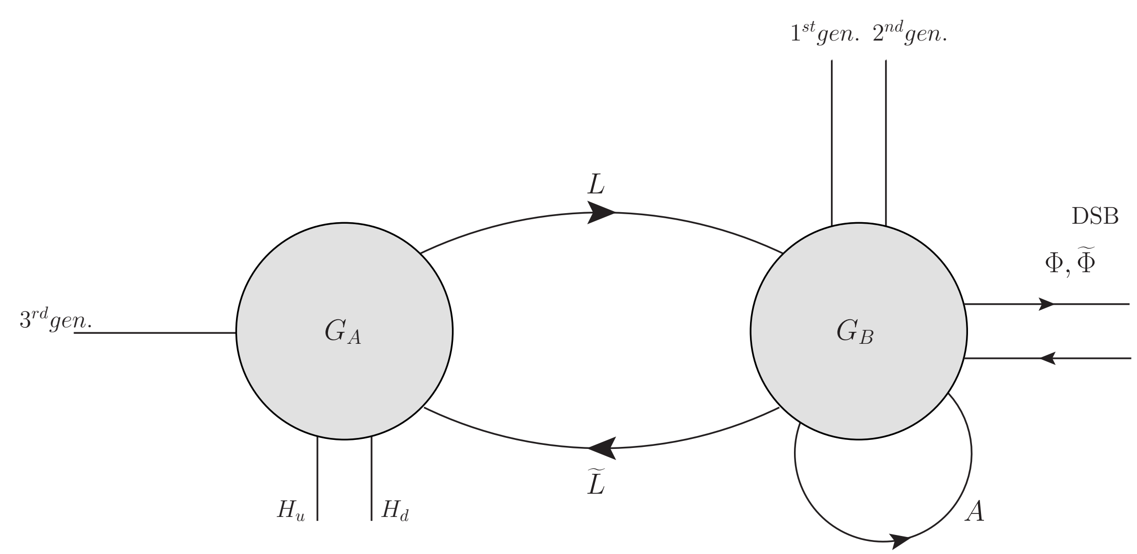

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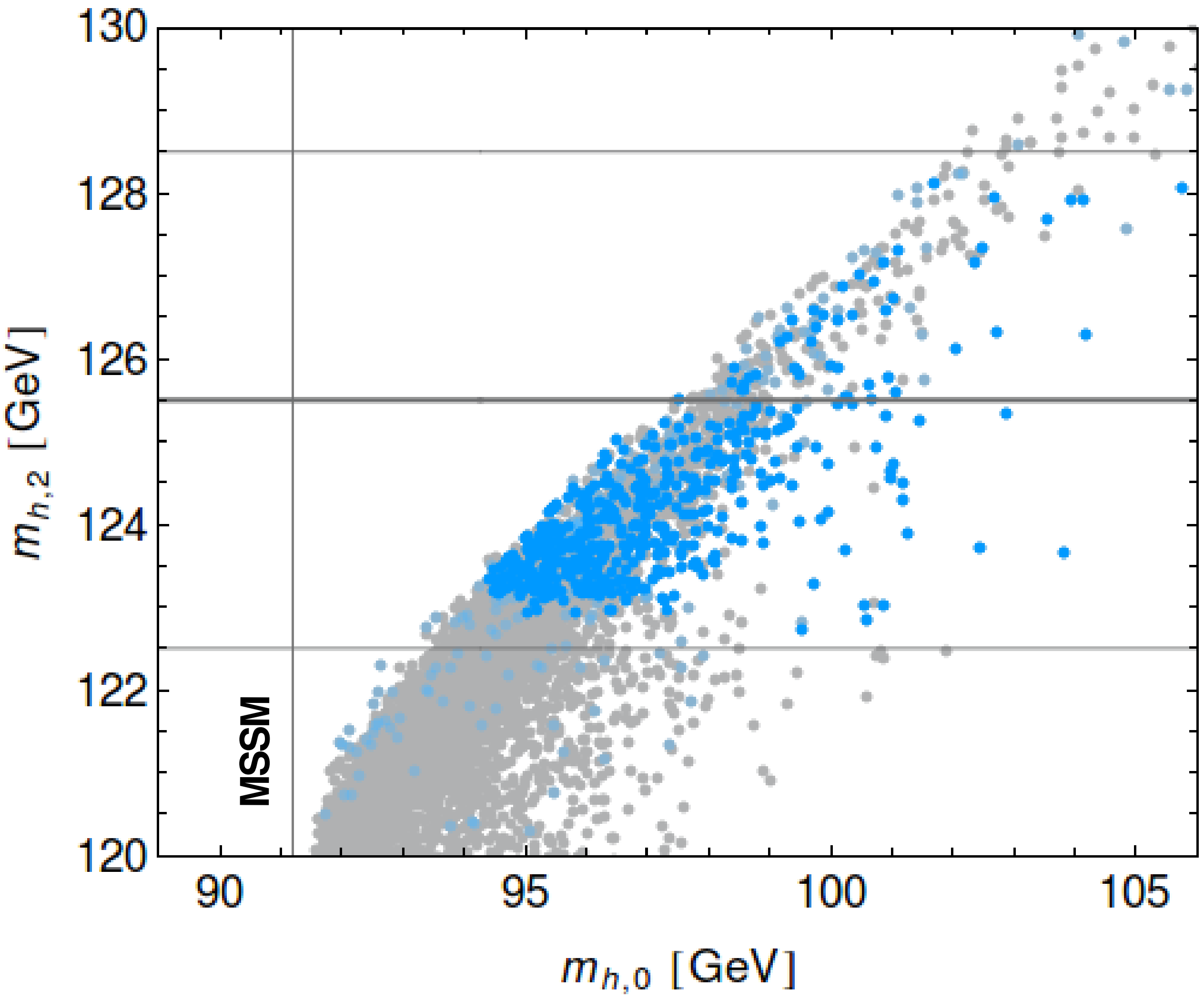
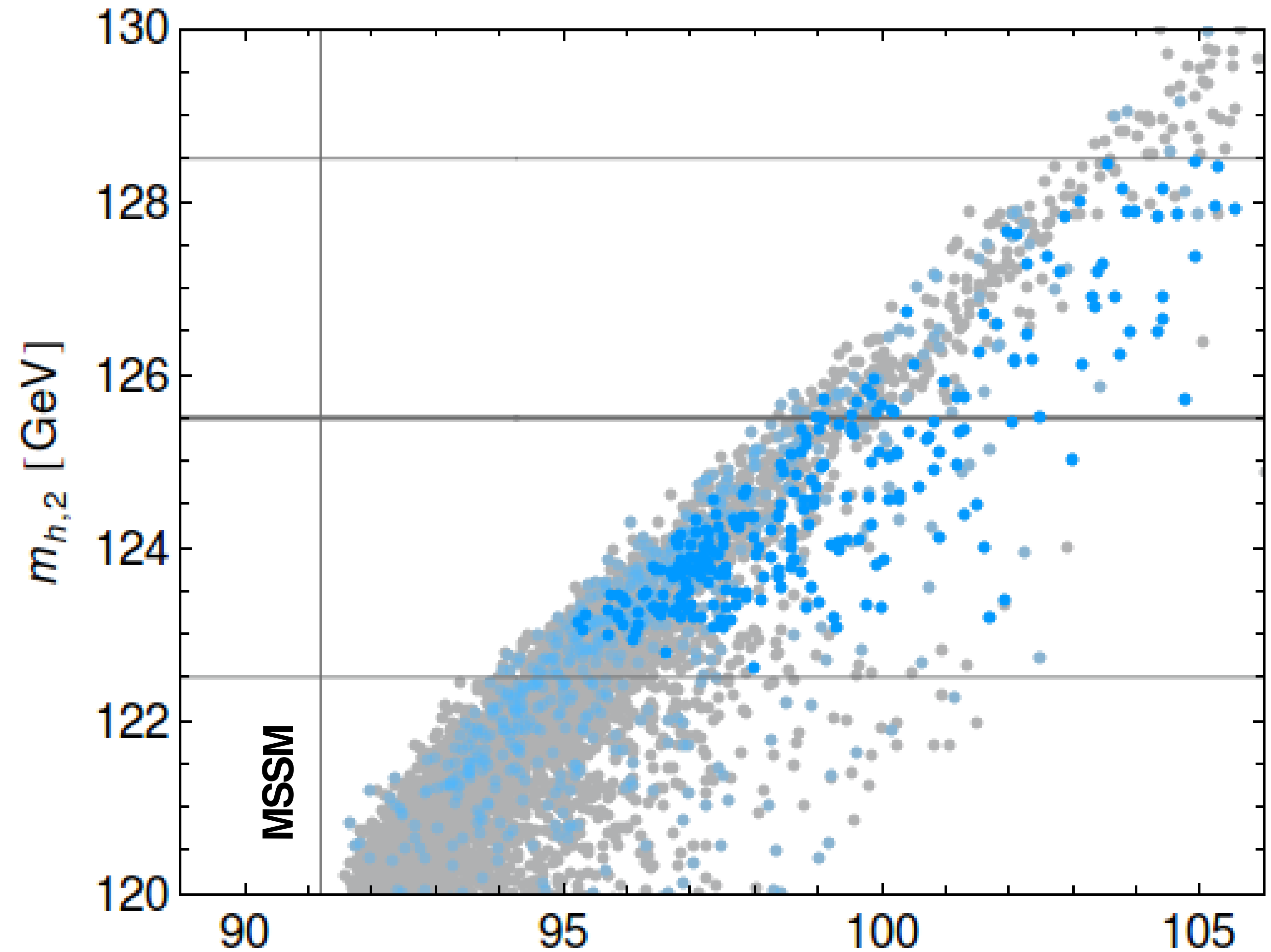
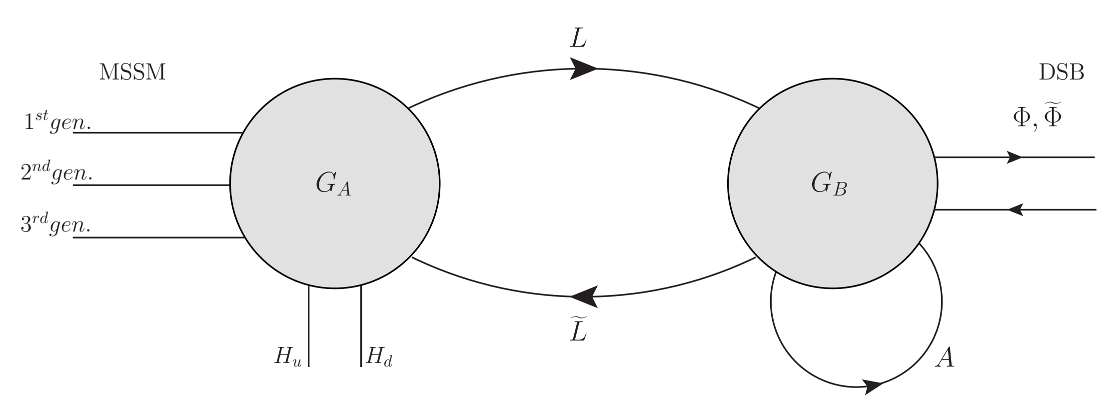
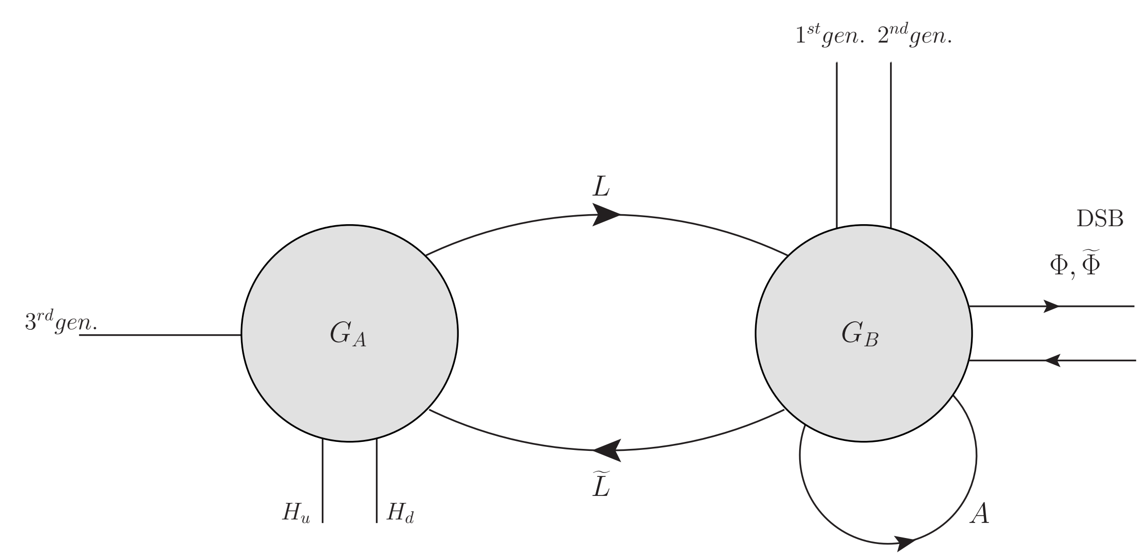
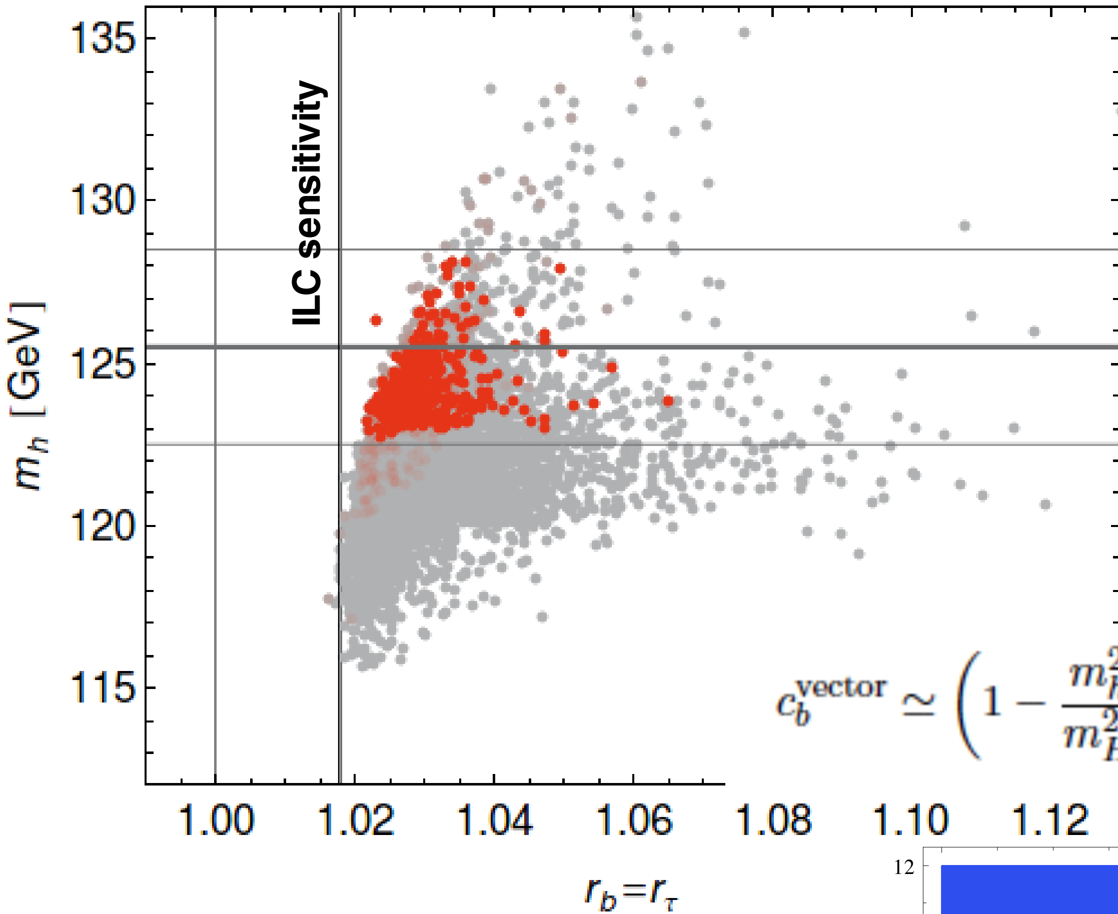


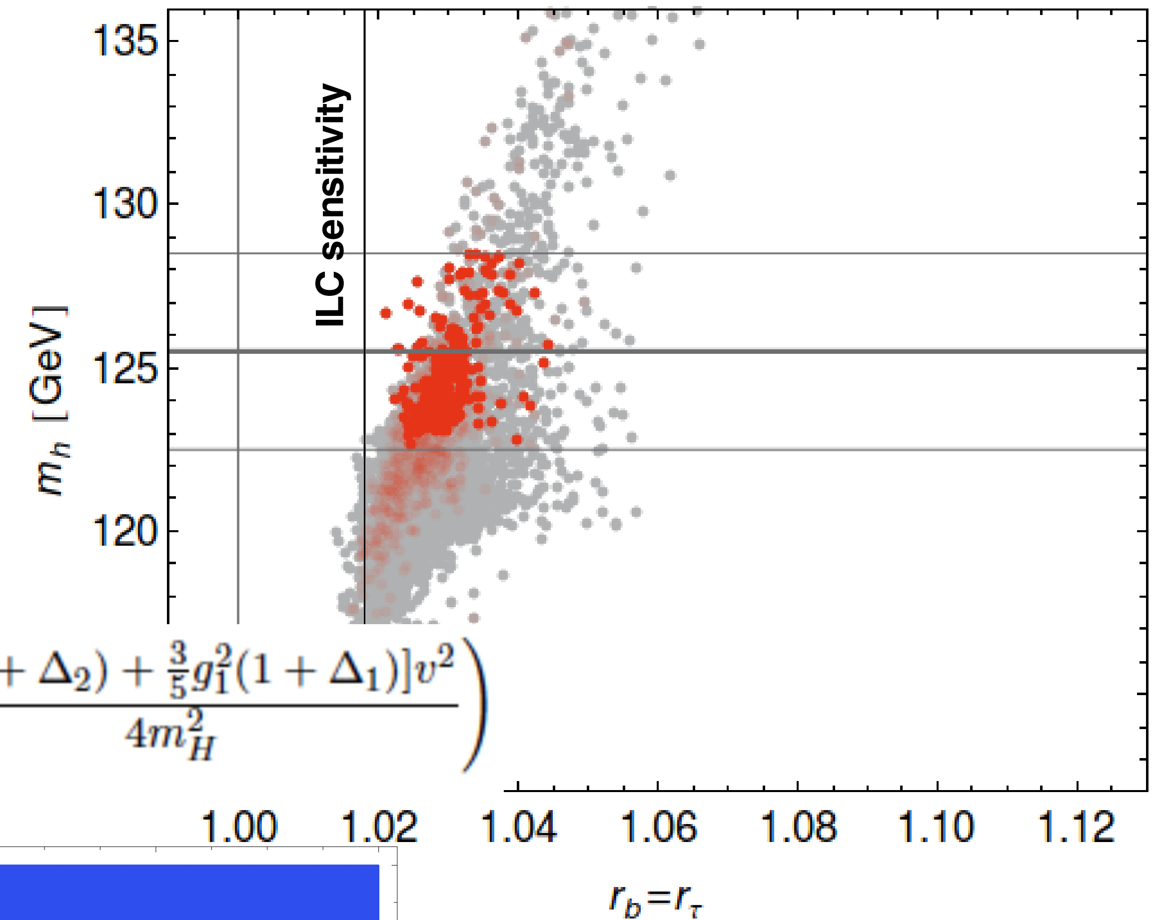




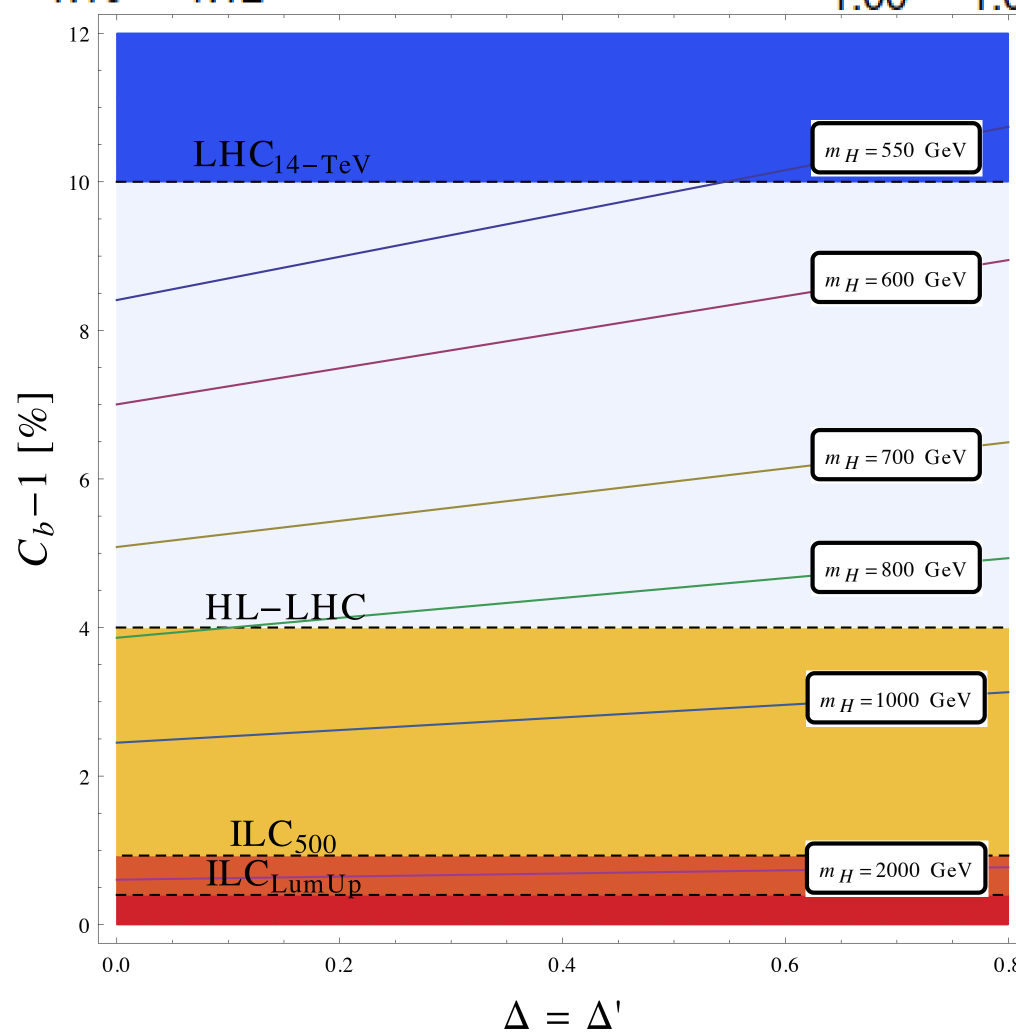


Testable at ILC!





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



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

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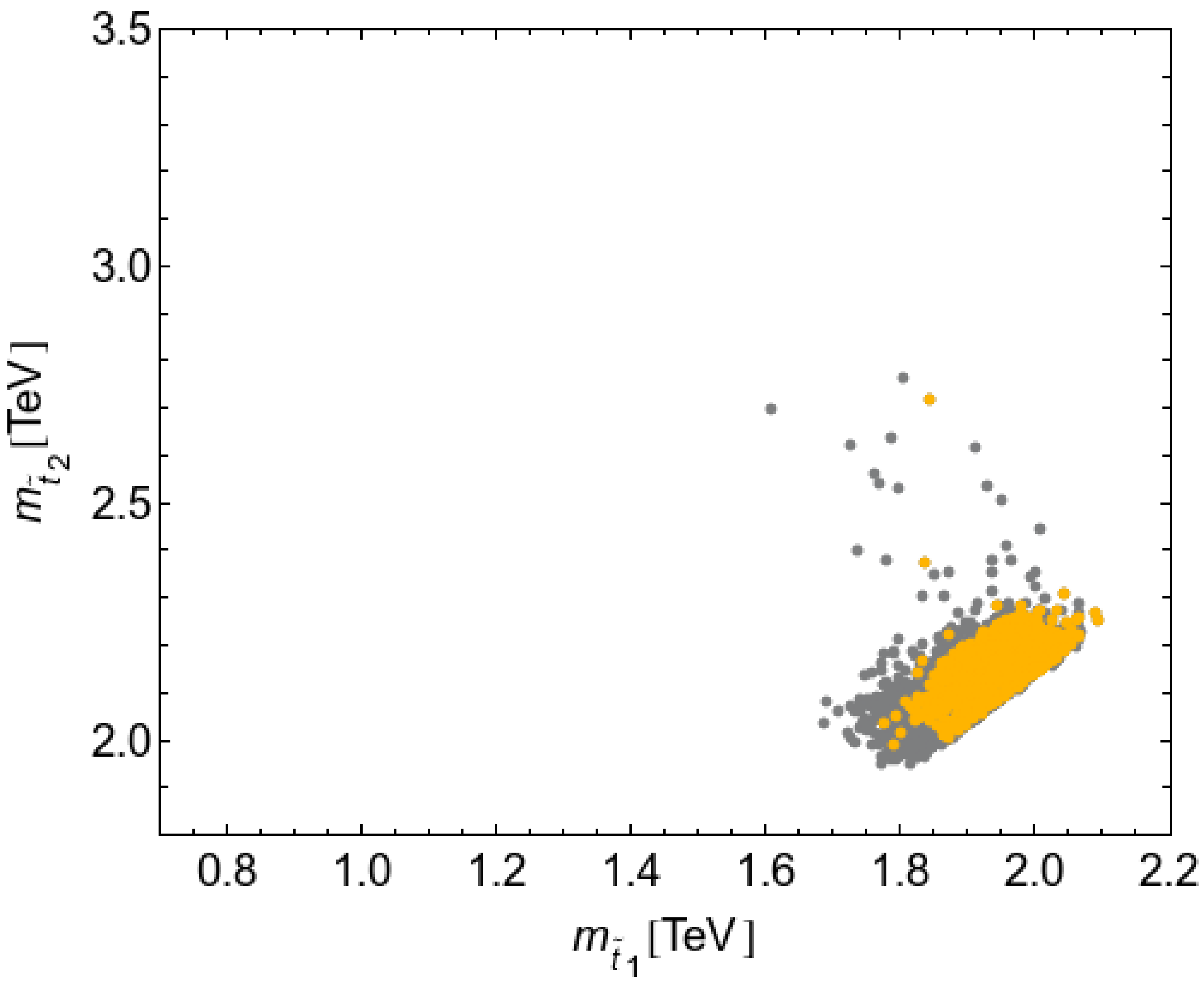
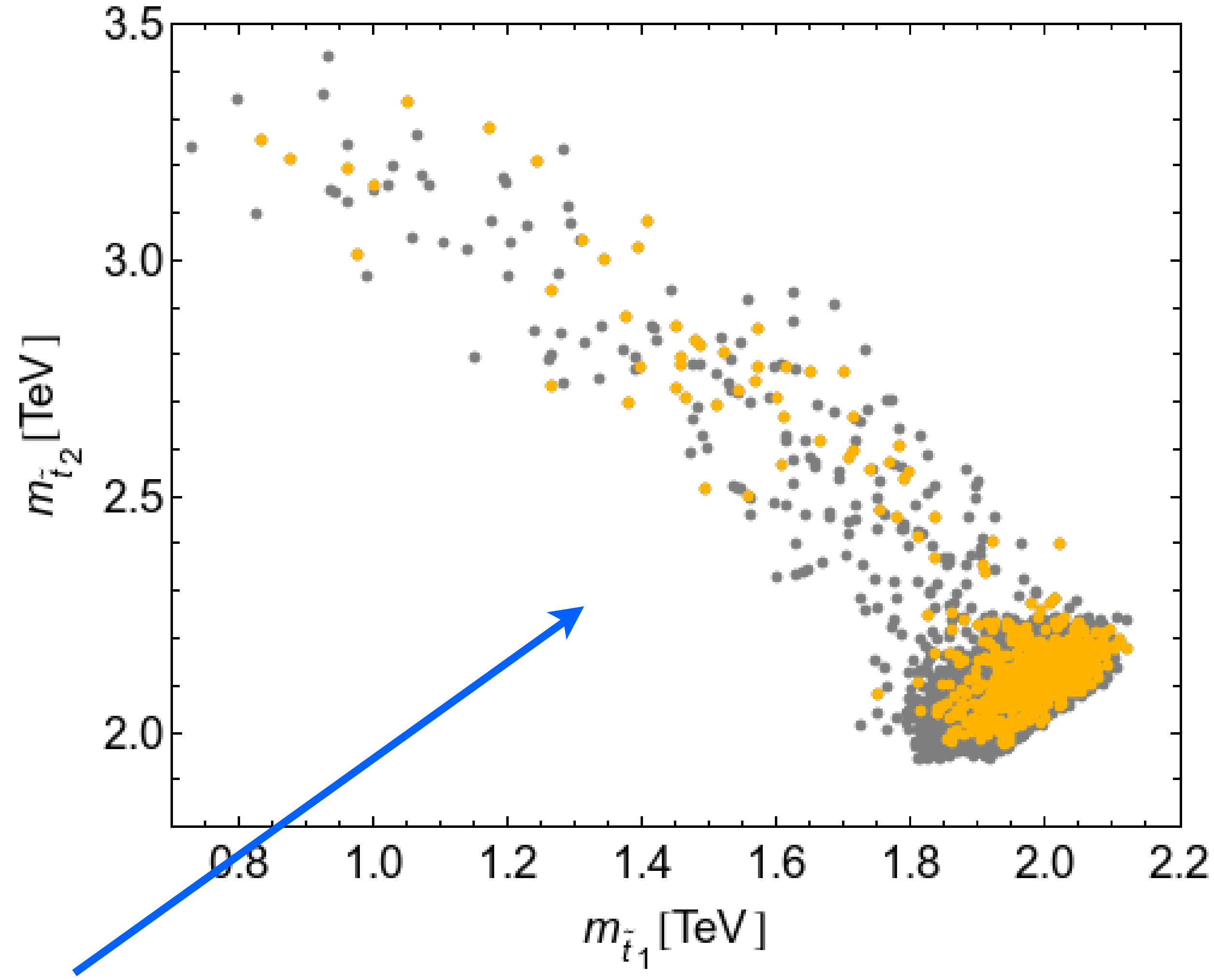
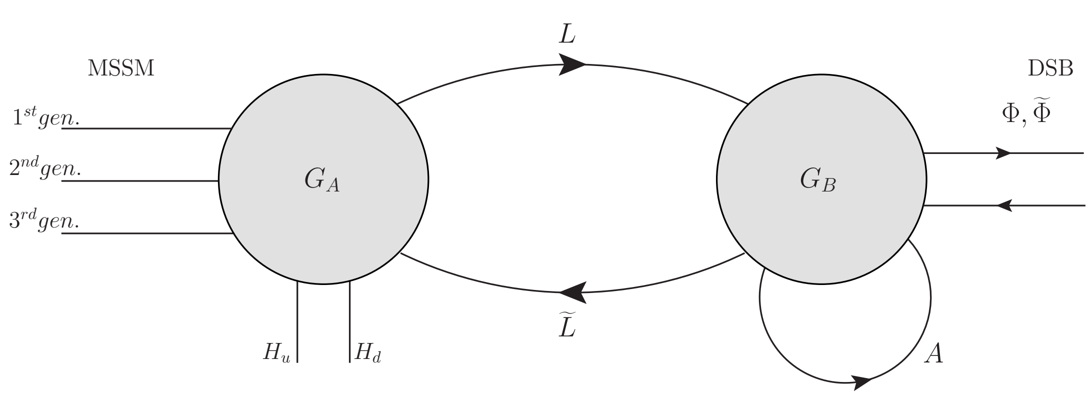
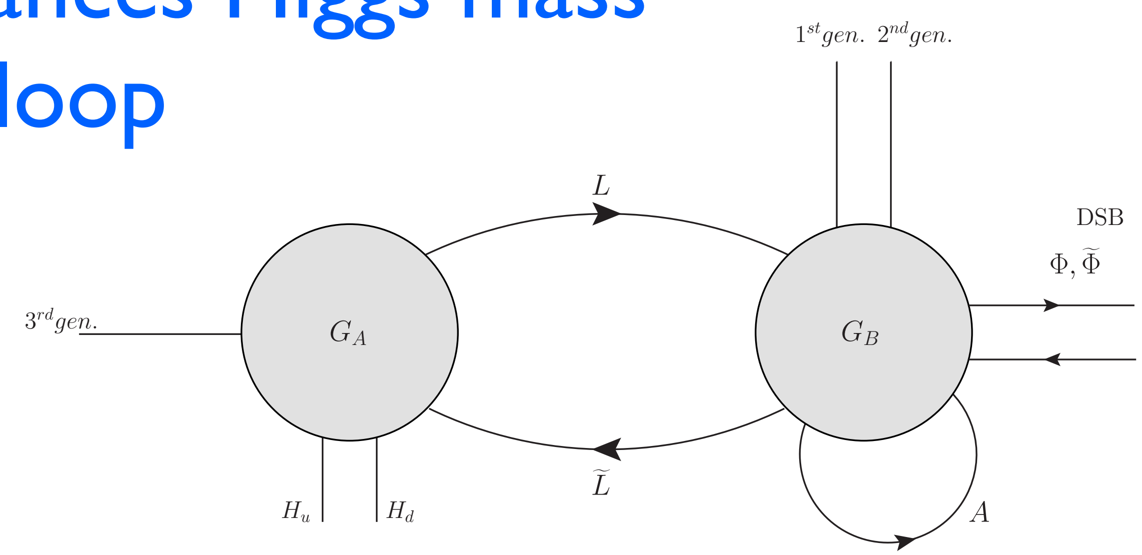
$$m_h^2 \simeq m_z^2\cos^2(2\beta) + \frac{3}{(4\pi)^2}\frac{m_t^4}{v_{ew}^2}\left[\log\frac{m_{\tilde t}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde t}^2}\left(1-\frac{X_t^2}{12 m_{\tilde t}^2}\right)\right] \quad + \Delta m_{h,1}^2 = \frac{3m_Z^2}{16\pi^2 v_{ew}^2}\left(1-\frac{8}{3}\sin\theta_W^2\right)\cos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





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

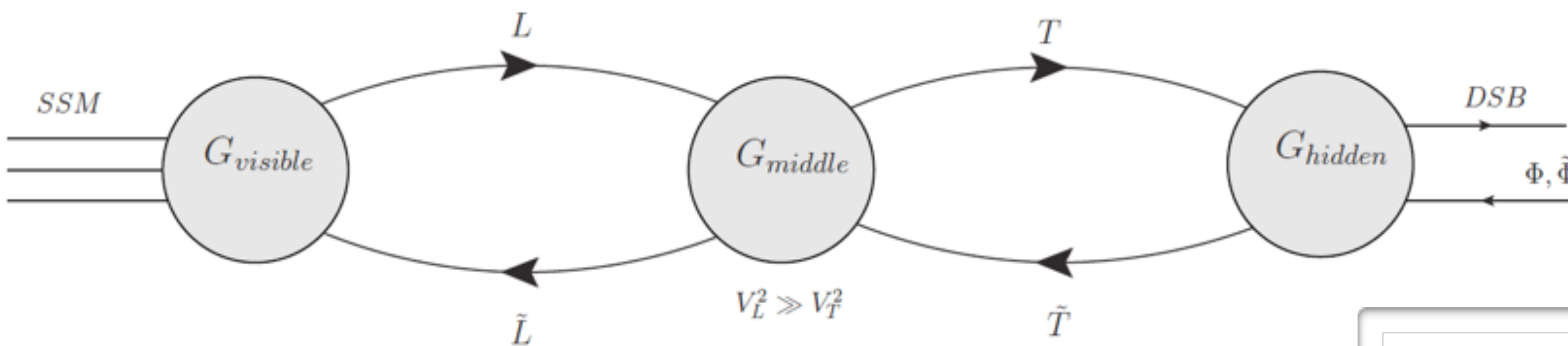
Can talk to FeynArts, Formcalc,CalcHep, Higgsignals, HiggsBounds, WHIZARD,microOMEGA,Vevacious and more

"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.*