SUSY Model Building for a 126 GeV Higgs

Moritz McGarrie

1.The Higgs mass 126 GeV

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

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

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

- Radiative corrections are same order as tree level piece
- Fine tuning effects all models: R-S, composite Higgs, little Higgs, SUSY etc
- corrections run logarithmically in SUSY
- MSSM case implies either heavy stops or large X_t=A_t +....

Fine tuning: little hierarchy problem

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

Light Higgsino and Wino

For a natural cancellation these should be of the same order

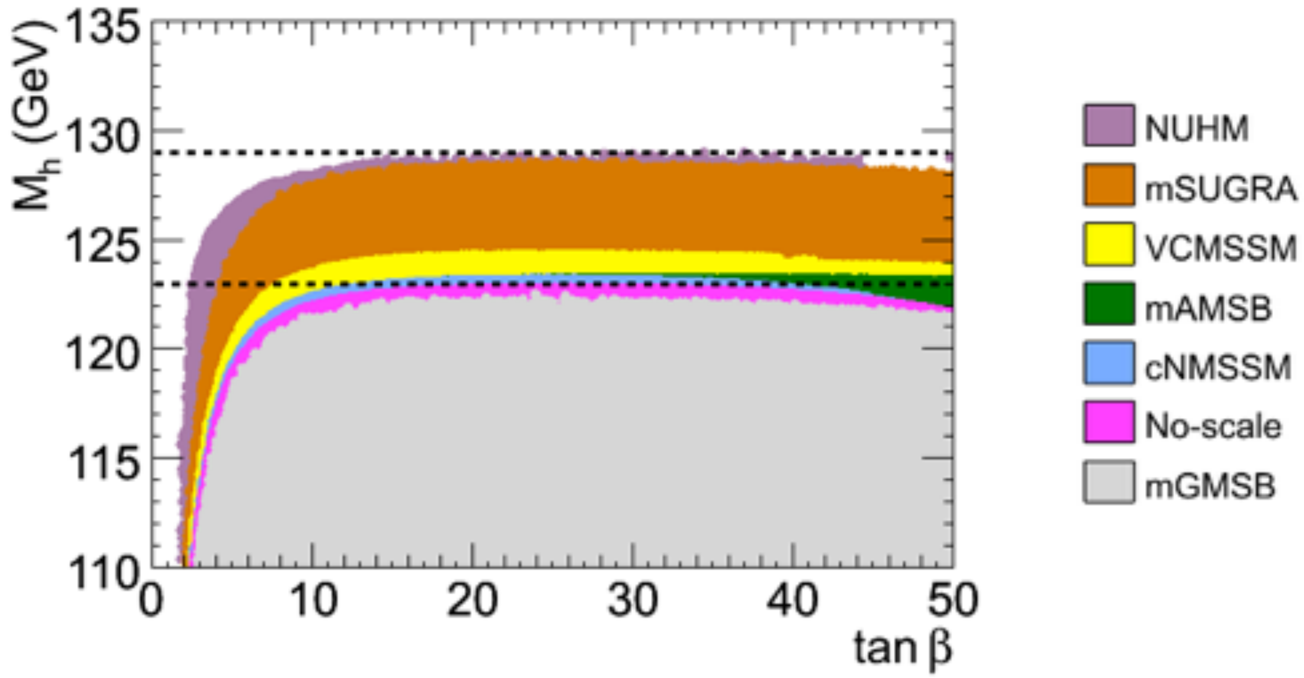
Light stops

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

Light(ish) Gluino

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

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 electric dipole moment, muon magnetic moment etc.
- MSSM bounds Higgs < 135 GeV

what are our choices?

The trivial / *Immoral option*

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

The hard / ugly / *unbelievable option*

Generate large At (vanishing in mGMSB, uncalculable in SUGRA and has other problems.)

The innovative *option*

or 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

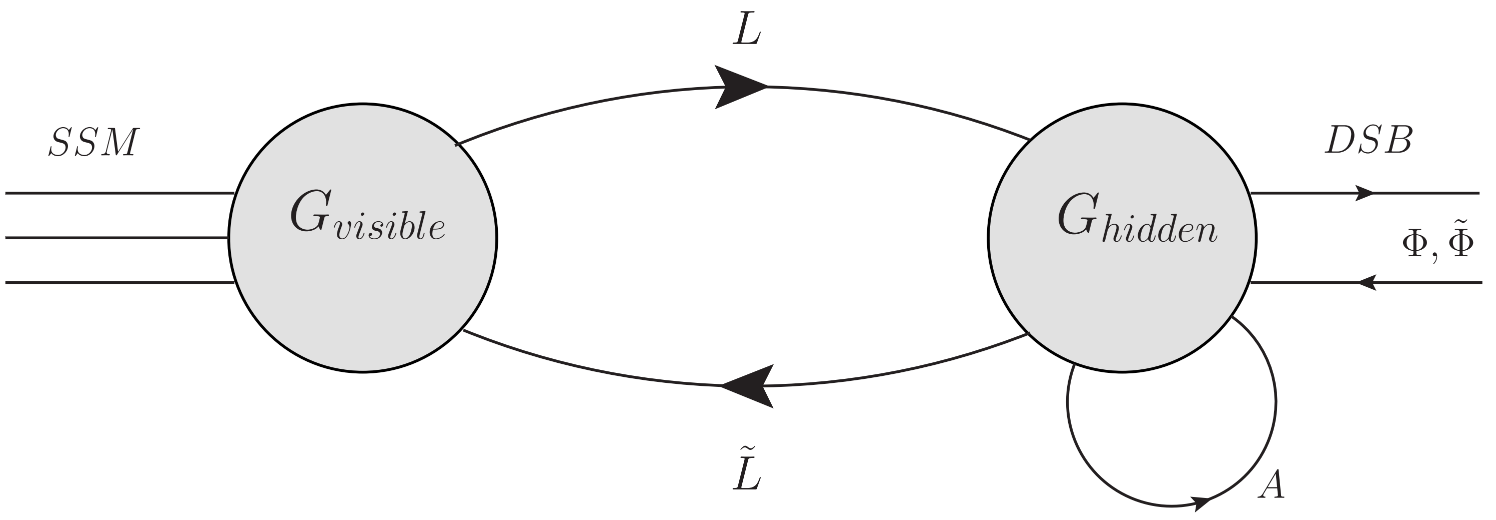
(F.Bruemmer, A.Weiler & MM) 1312.0935

(S.Abel & MM) 1404.1318

(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

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

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

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

S.Abel, M. Goodsell

Bharucha, Goudelis, M.M. 1310.4500

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

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

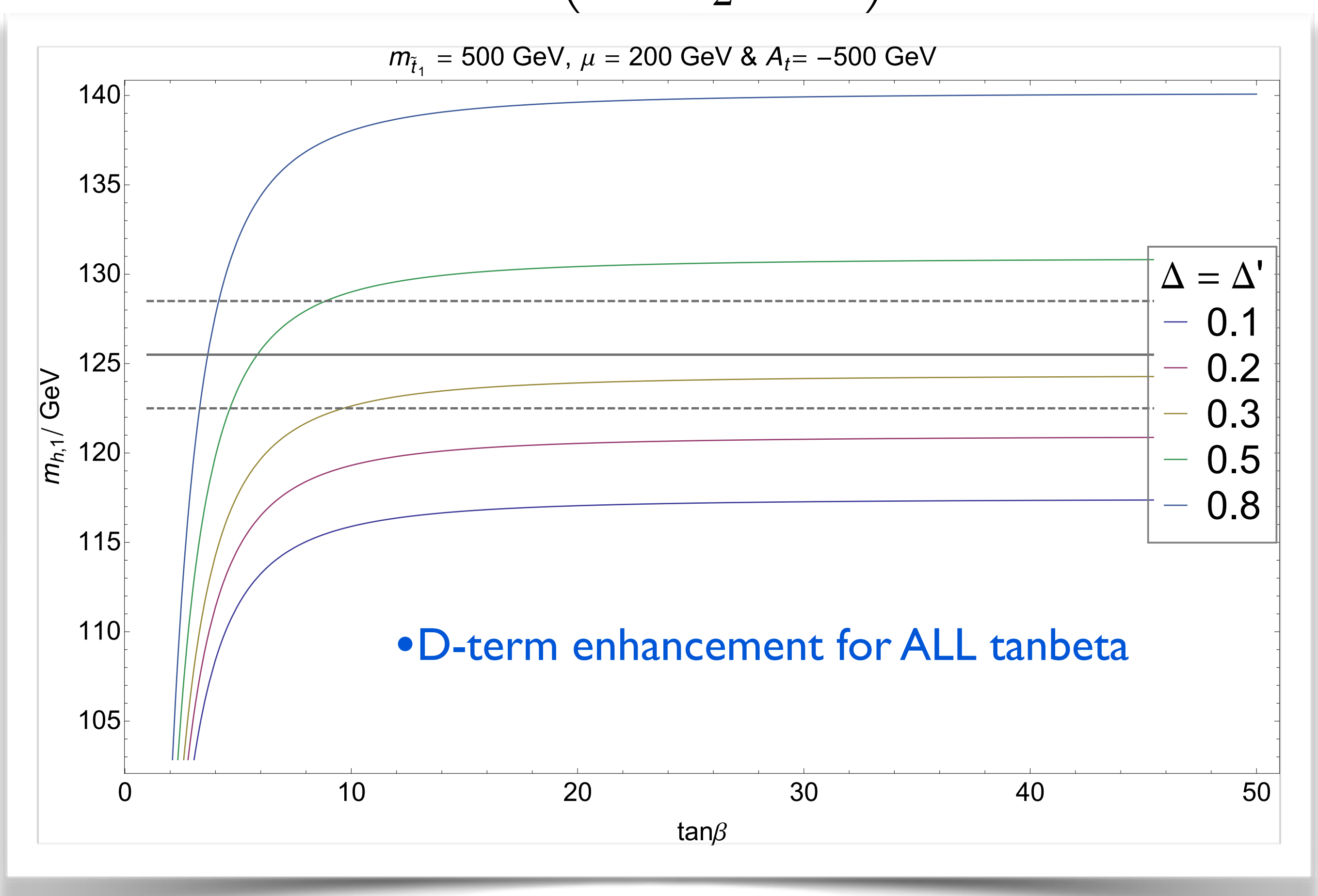
D-terms Vs NMSSM

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

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

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

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



- D-term enhancement for ALL tanbeta

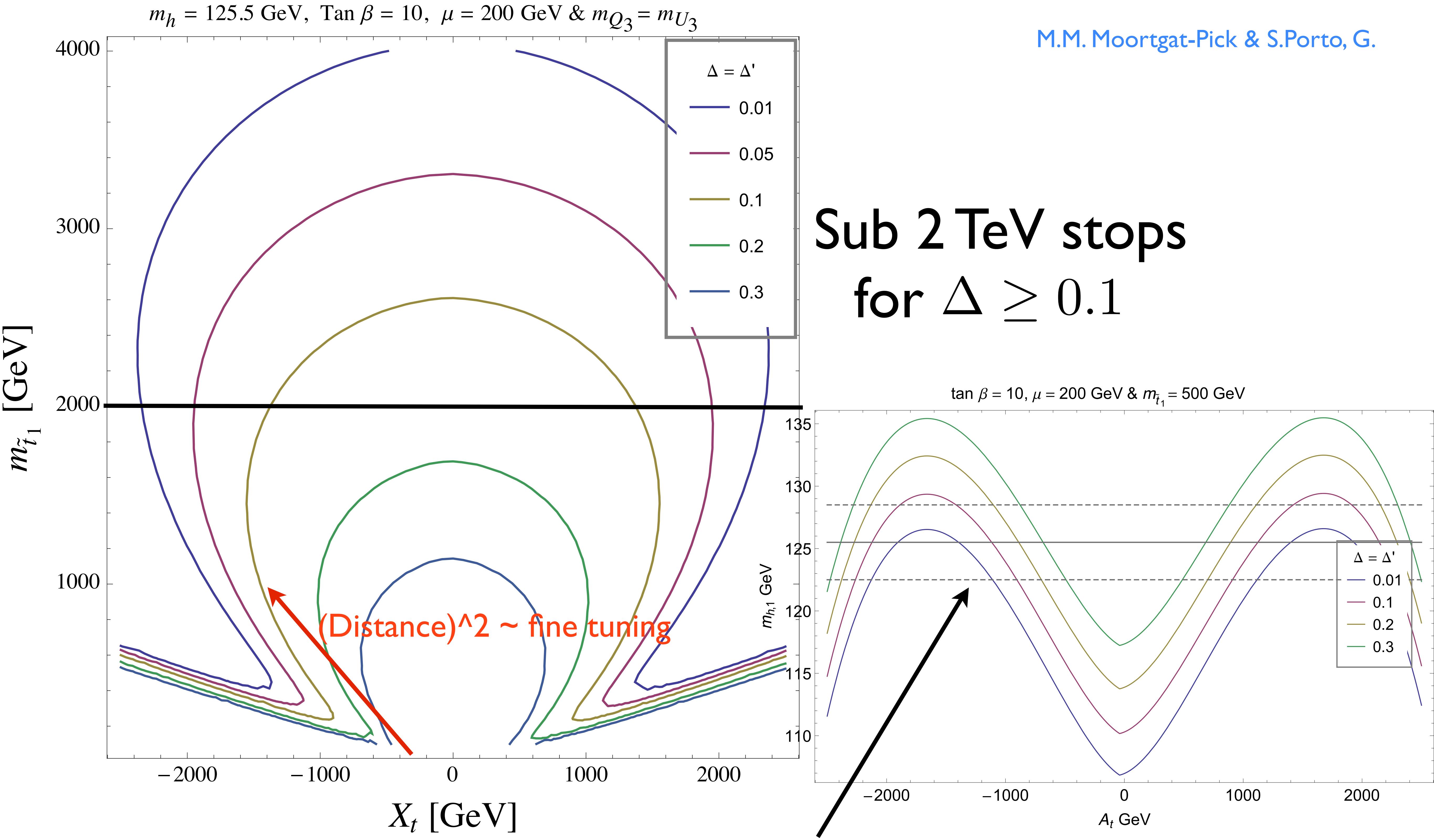
$$W_{NMSSM} \supset \lambda S H_u H_d$$

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

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

- 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?)

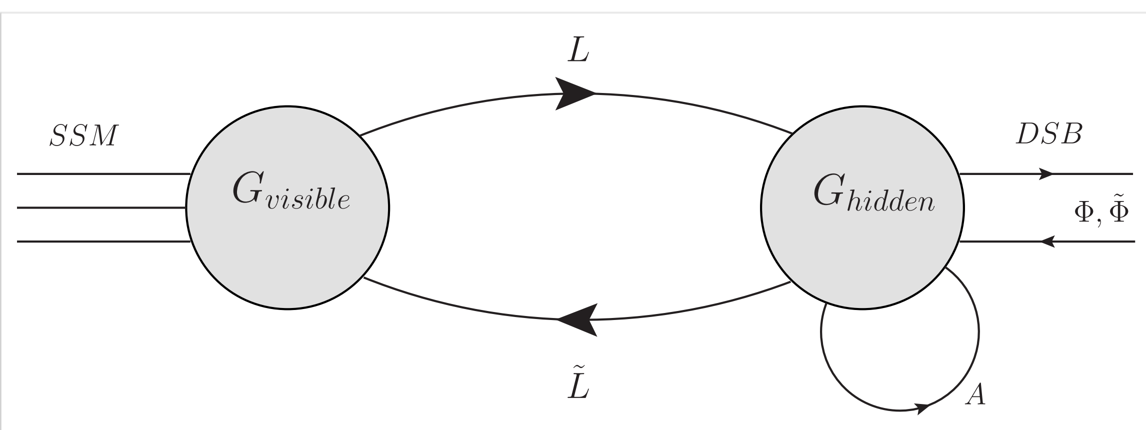
So far most studies of D-terms have been at tree-level and bottom-up ....

A *meta* model

Bharucha, Goudelis, M.M. 1310.4500

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.



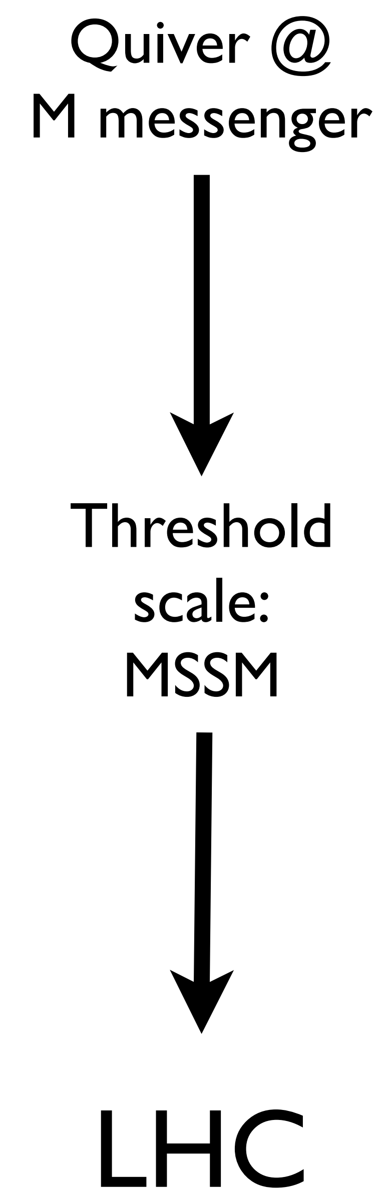
$$W_{\mathrm{SSM}} = Y_u\, \hat{u}\, \hat{q}\, \hat{H}_u - Y_d\, \hat{d}\, \hat{q}\, \hat{H}_d - Y_e\, \hat{e}\, \hat{l}\, \hat{H}_d + \mu\, \hat{H}_u\, \hat{H}_d$$

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

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?

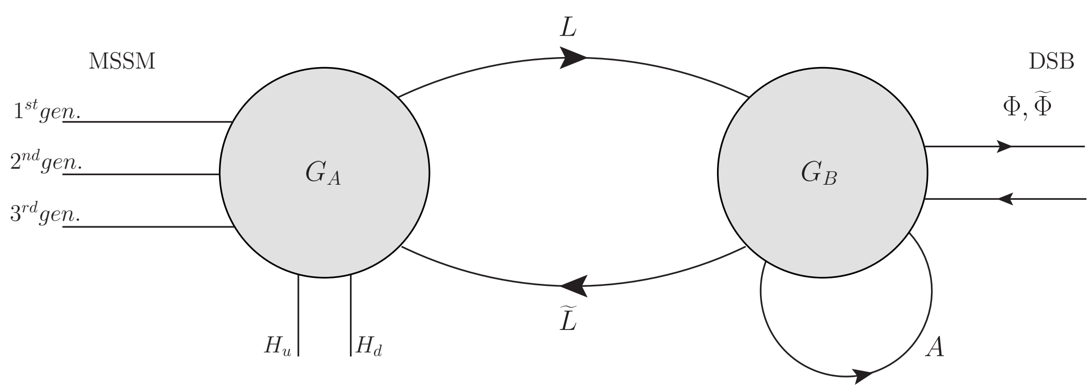
Building a taylor made spectrum generator!

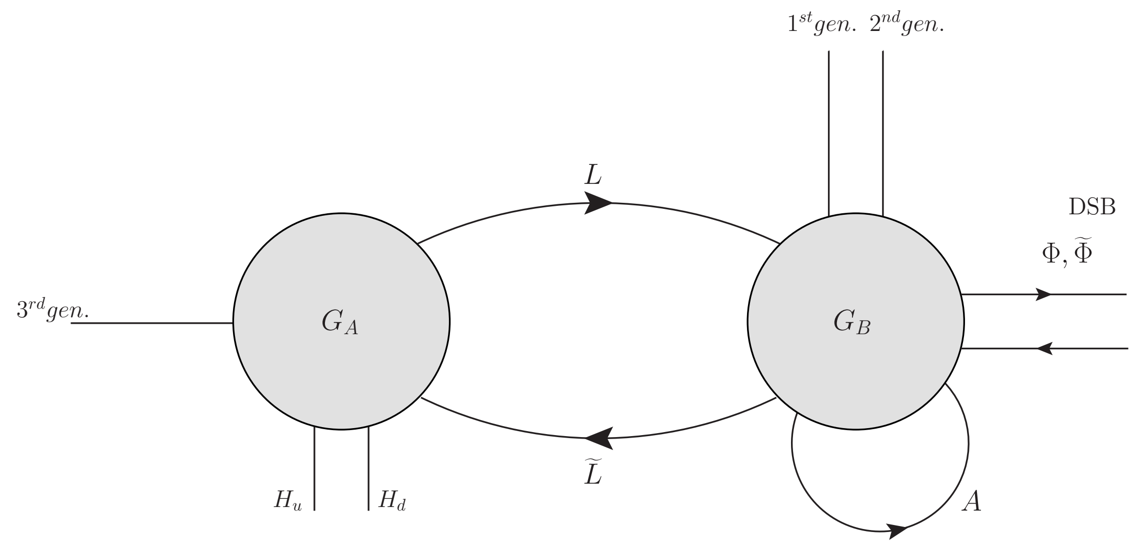
- We used SARAH mathematica package: "a spectrum generator *generator*" to write our own spectrum generator.
- We implemented 5 gauge groups with full 2-loop RGE's and one loop self energies (soon 6 and 9 gauge groups!).
- Higgsing, and breaking to the diagonal 4 gauge groups, including all mixing matrices 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.

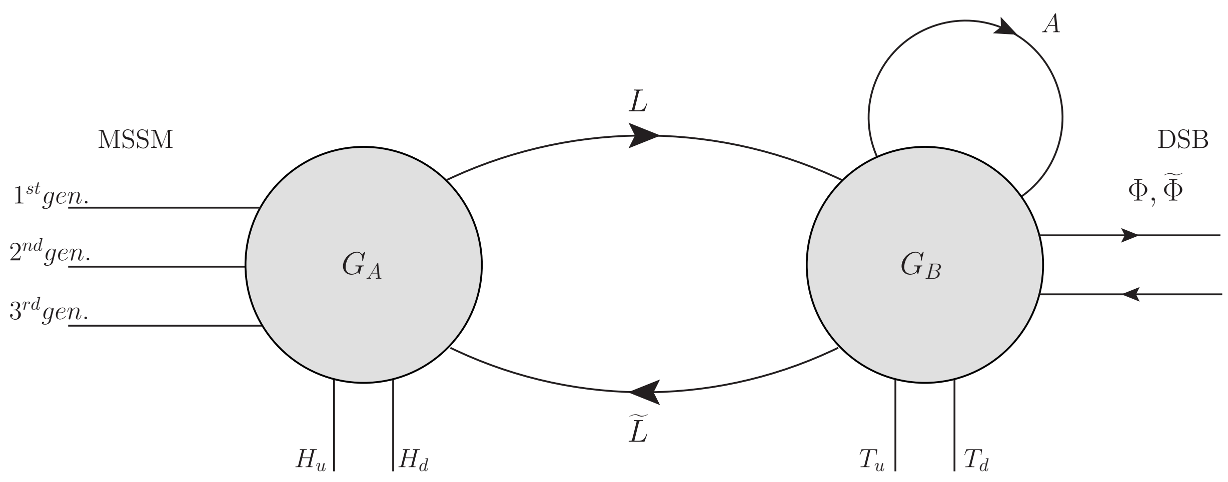


Bharucha,Goudelis, M.M. 1310.4500

The Quiver Variations





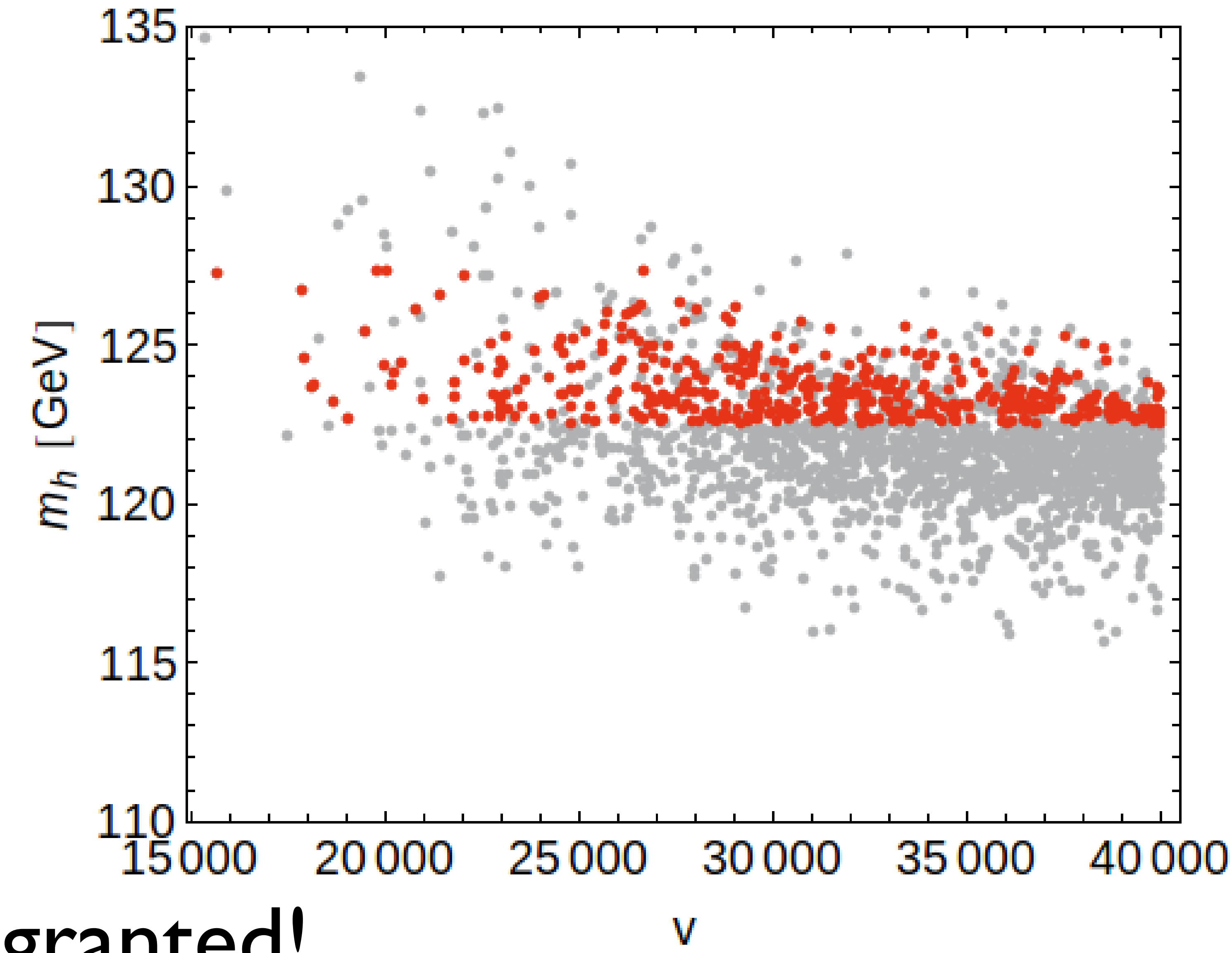


Wish list

- $v < 10\text{TeV}$

  $m_L^2 > m_v^2$

We assumed GMSB for soft terms!



Our wishes were not granted!

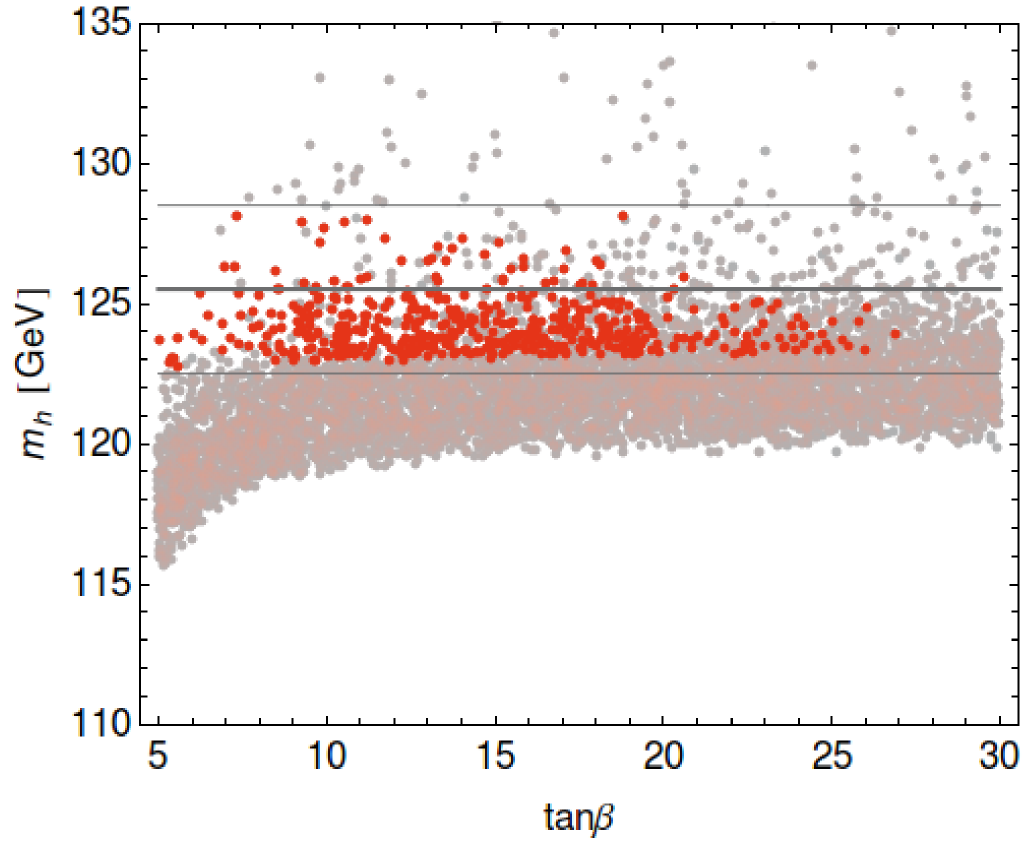
we had to enlarge m_L^2 to make it work

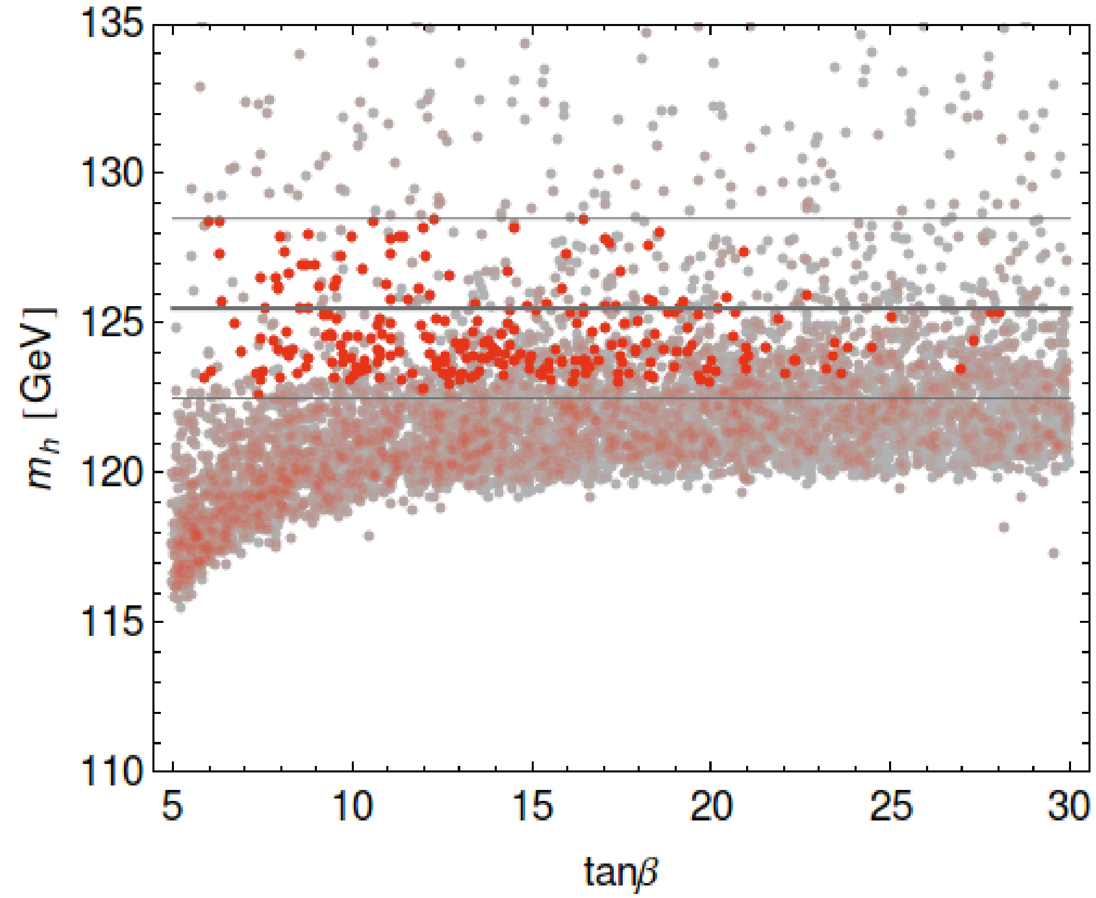
But perhaps this can be improved by considering different SUSY breaking scenarios

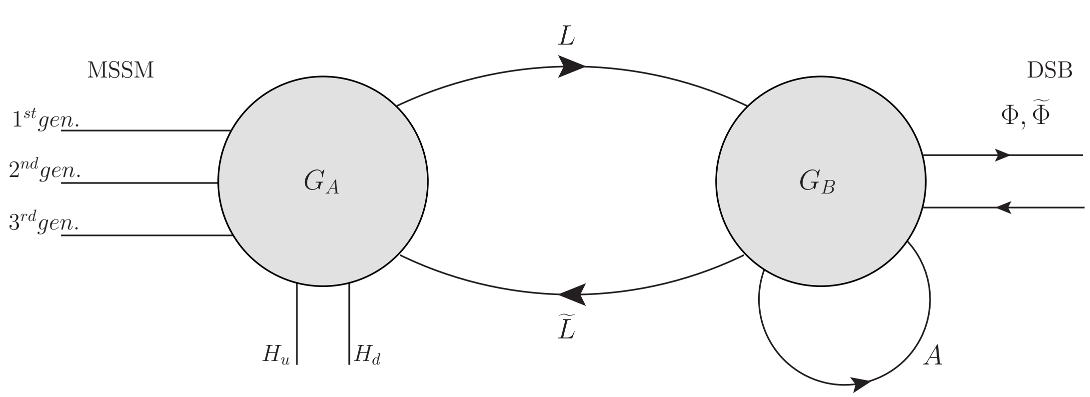
Ex. Applying mSUGRA here may get v down

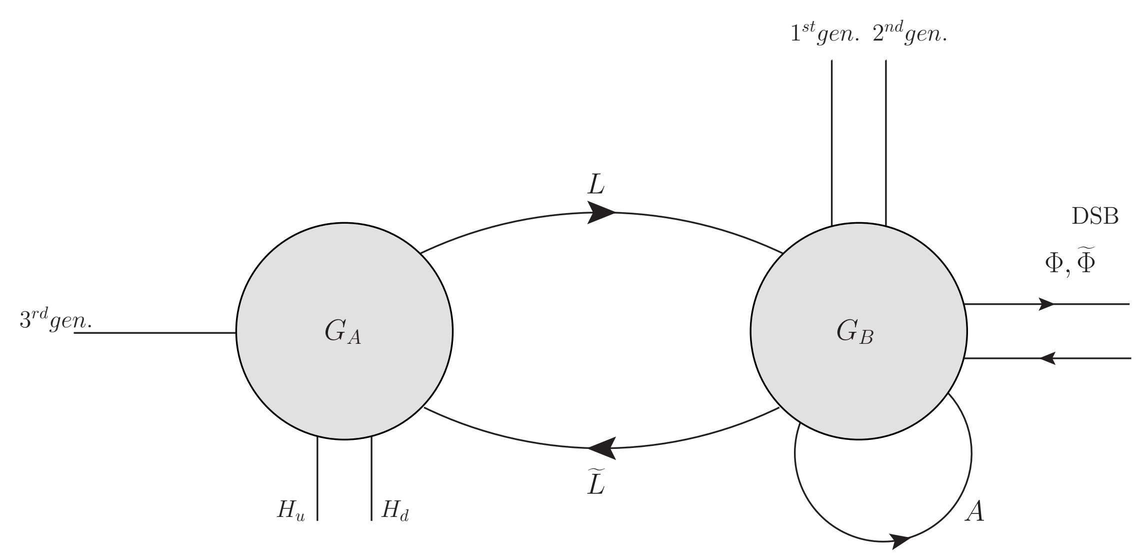
Bharucha, Goudelis, M.M. 1310.4500

Bharucha,Goudelis, M.M. 1310.4500

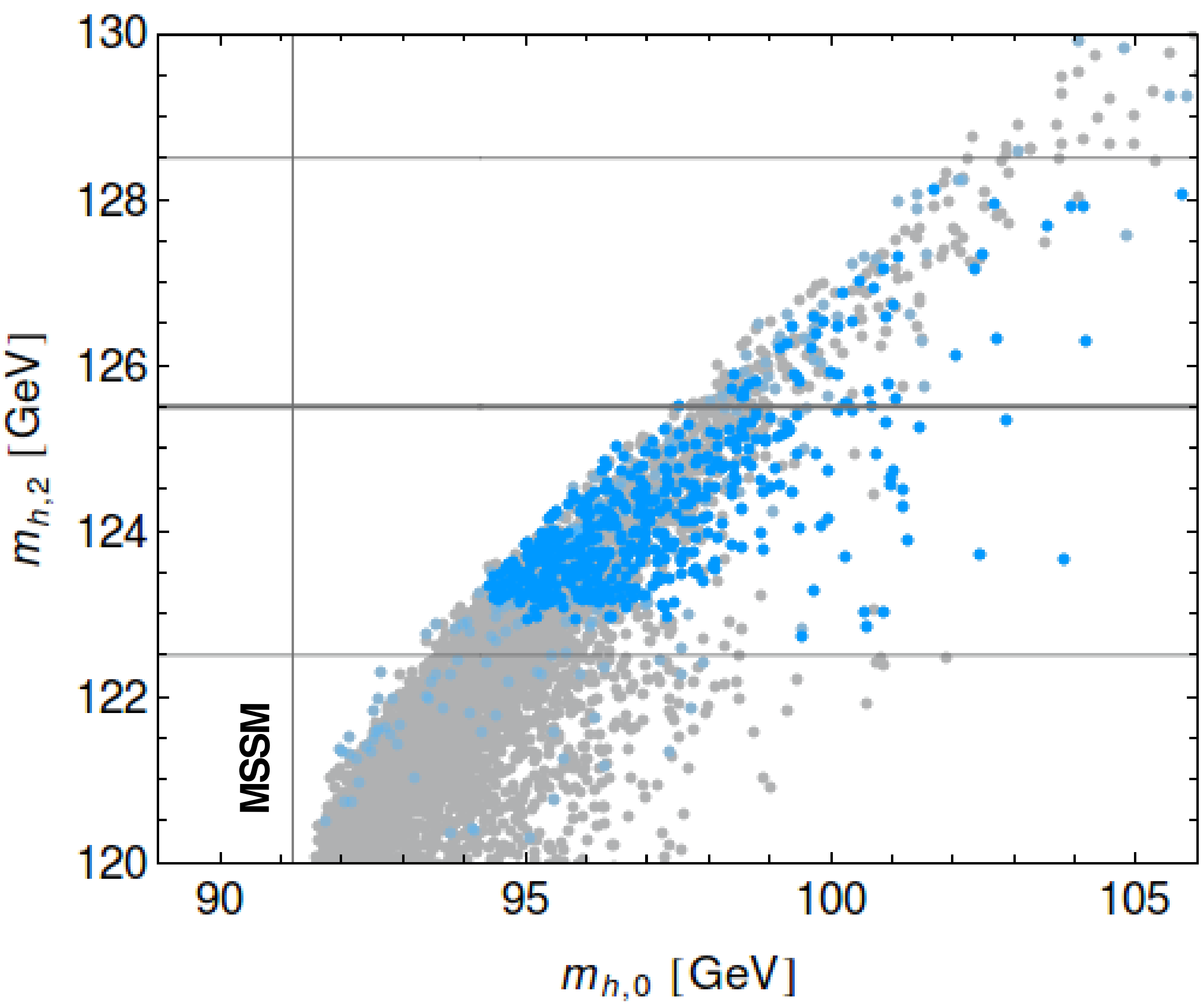


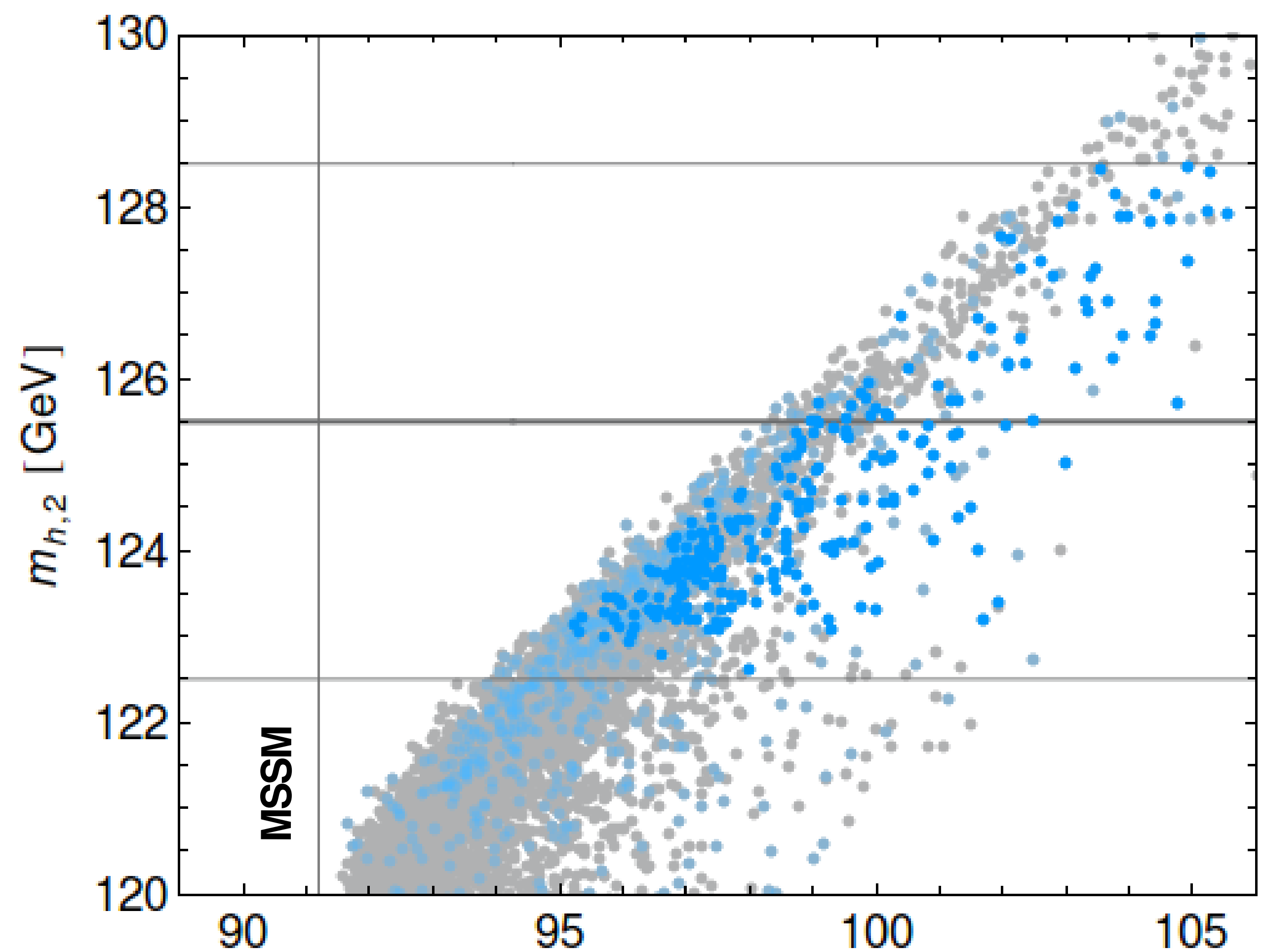


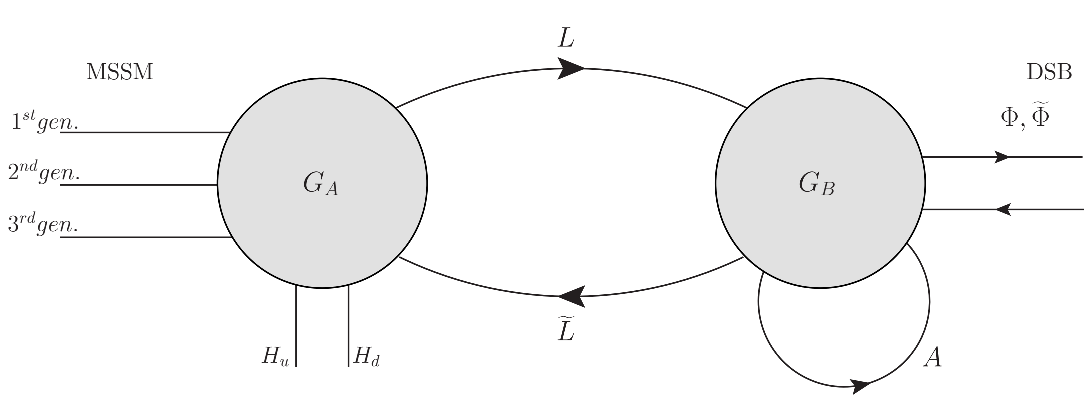


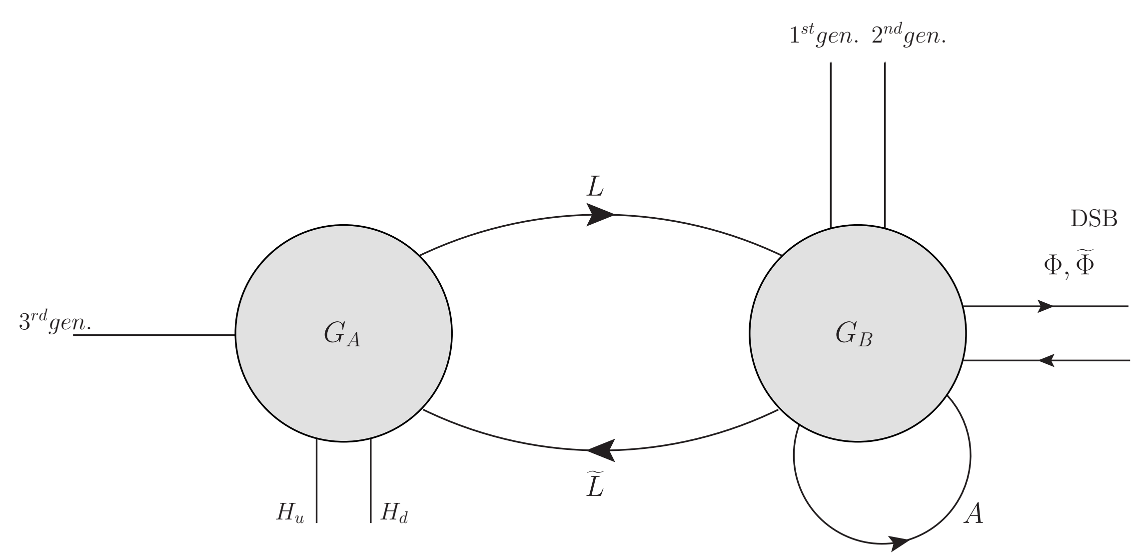


Bharucha,Goudelis, M.M. 1310.4500

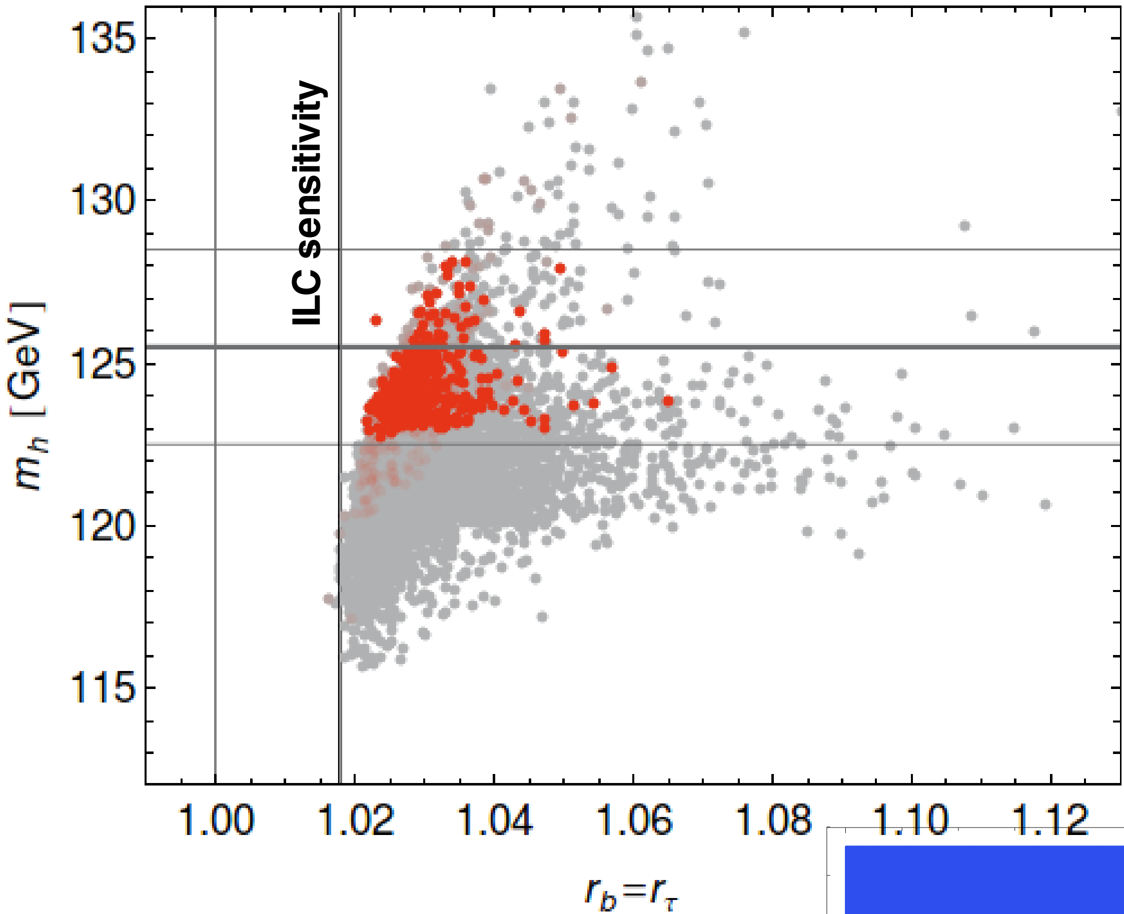


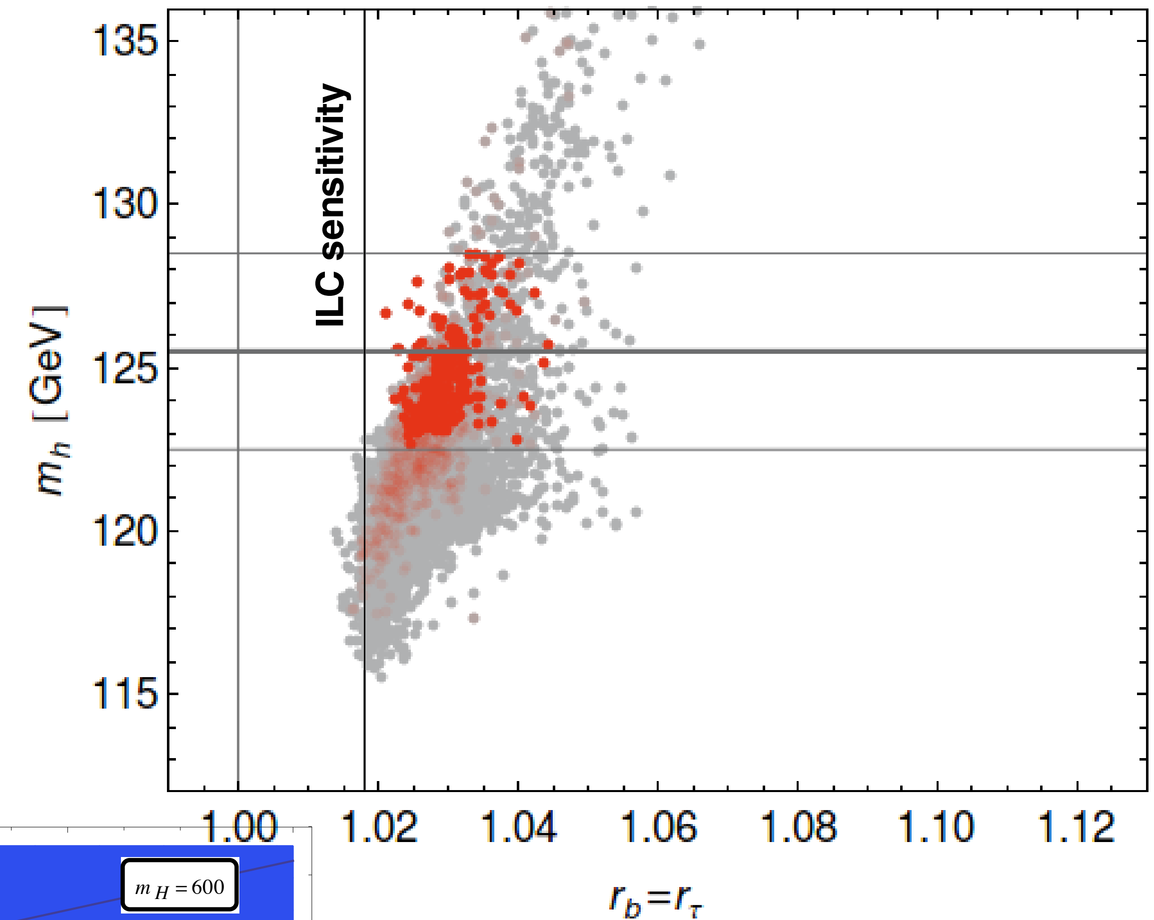


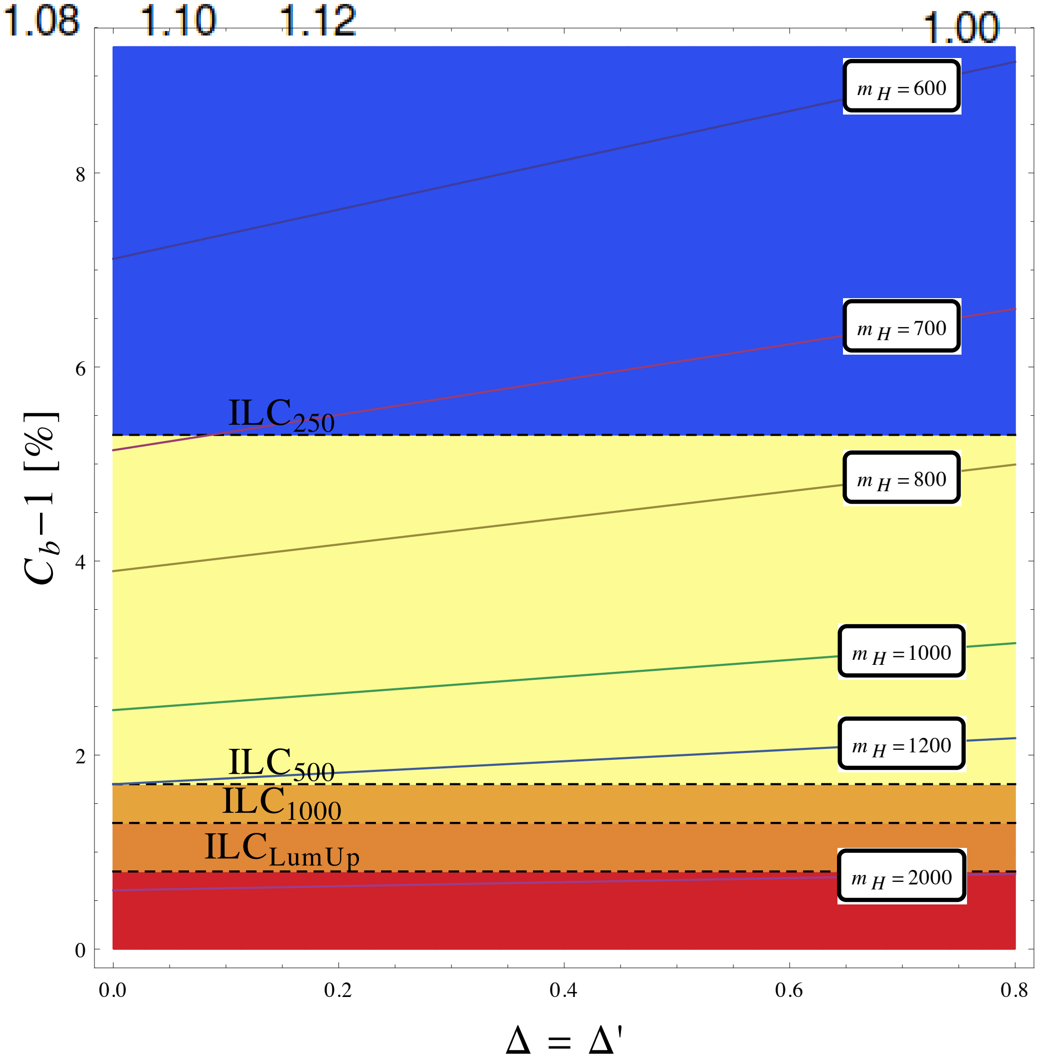




Testable at ILC!



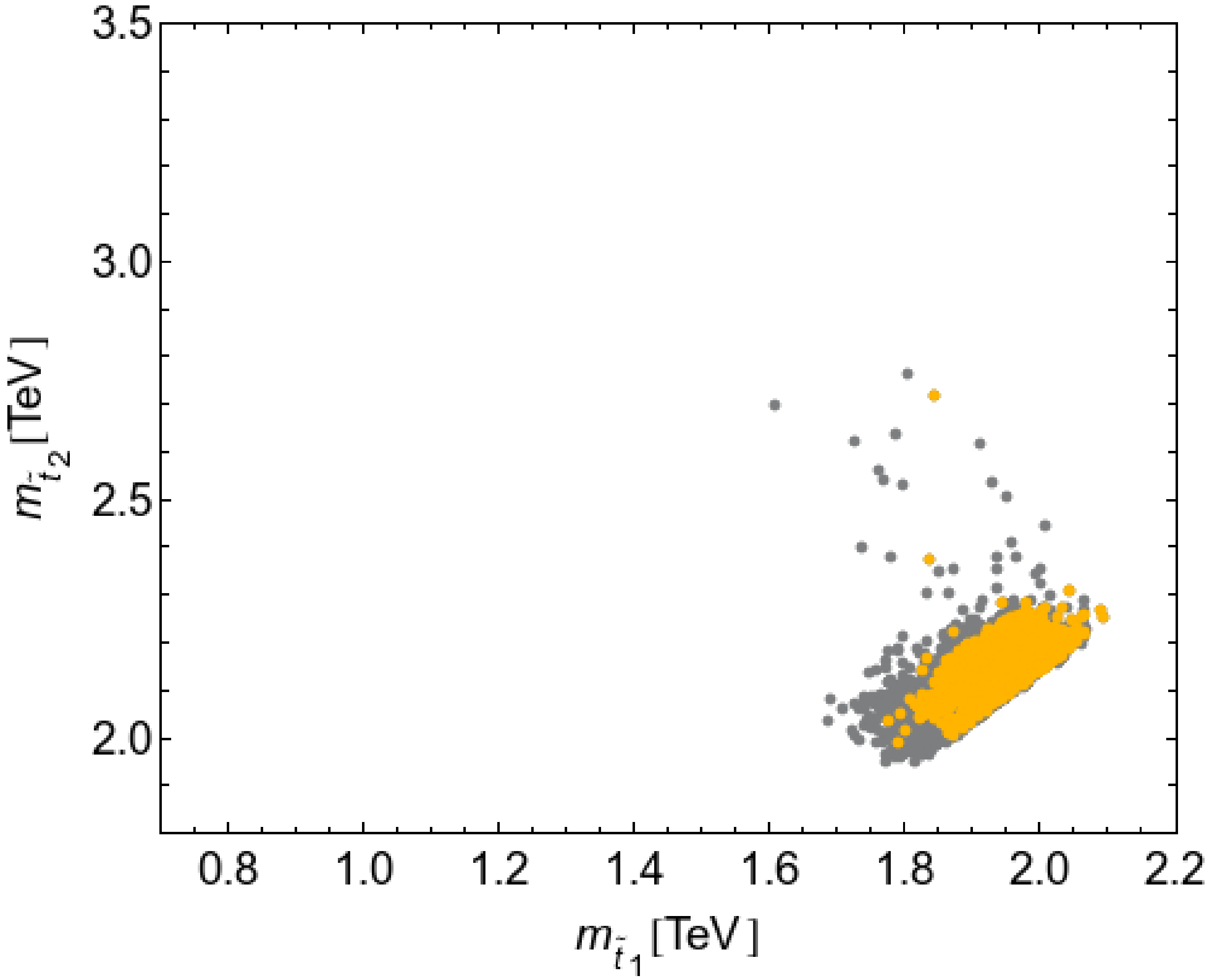


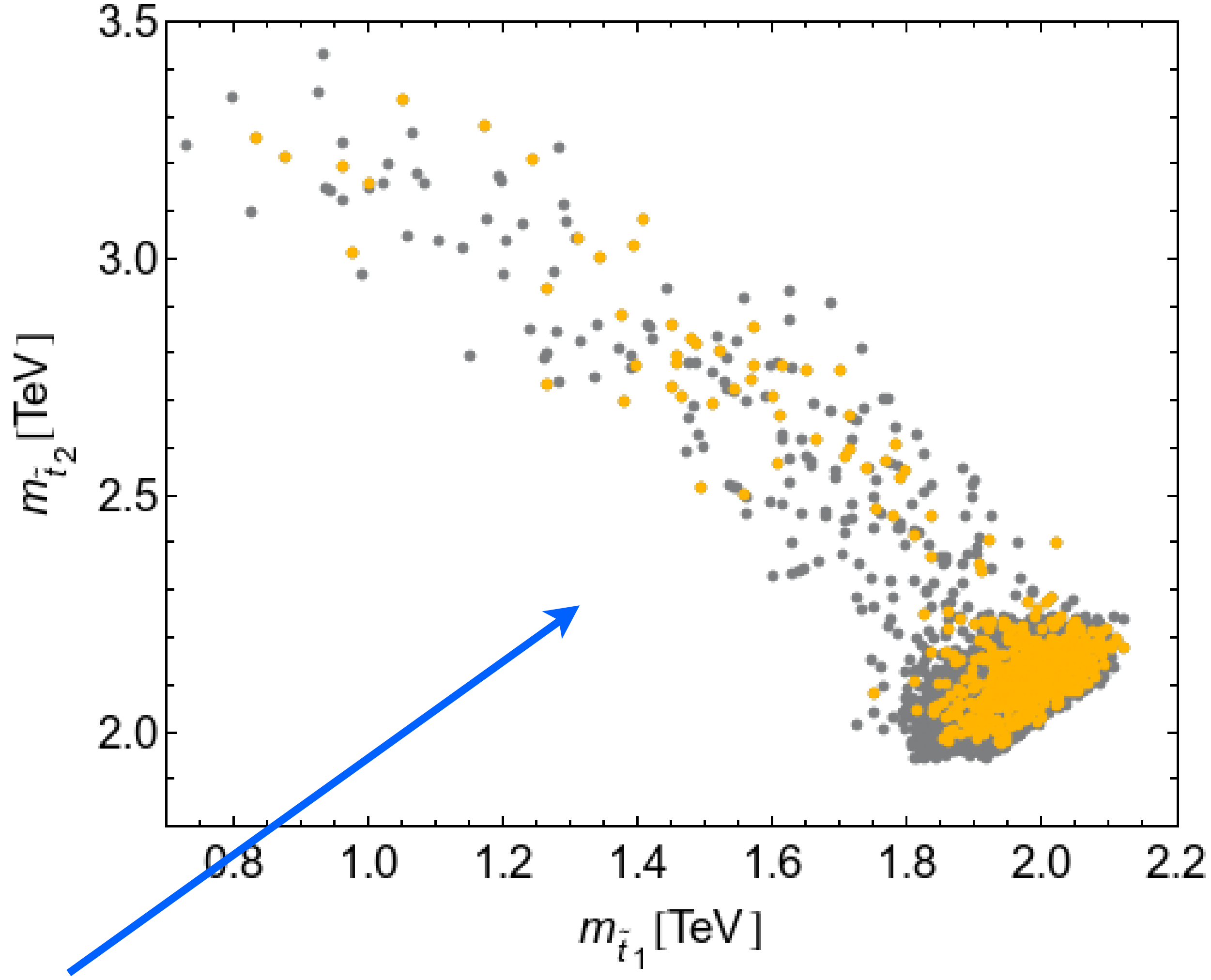


Testing D-terms
@ILC
with S.Porto, G. Moortgat-Pick (DESY)

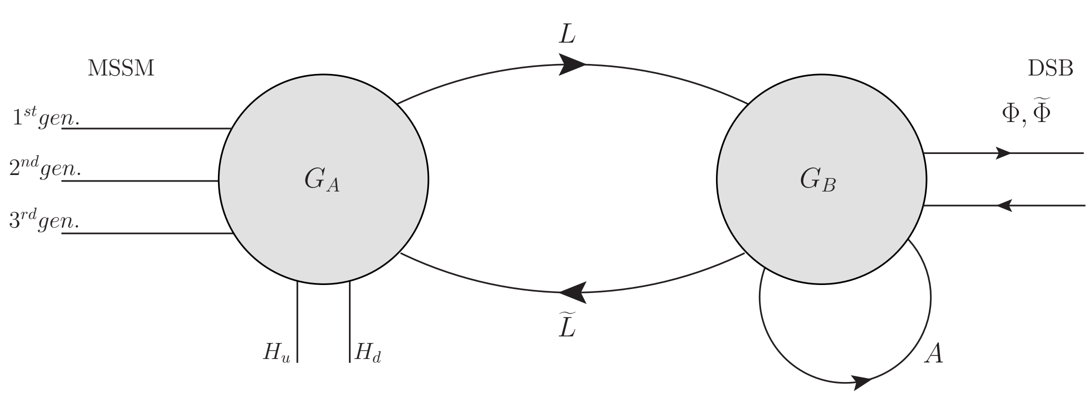
Bharucha, Goudelis, M.M. 1310.4500

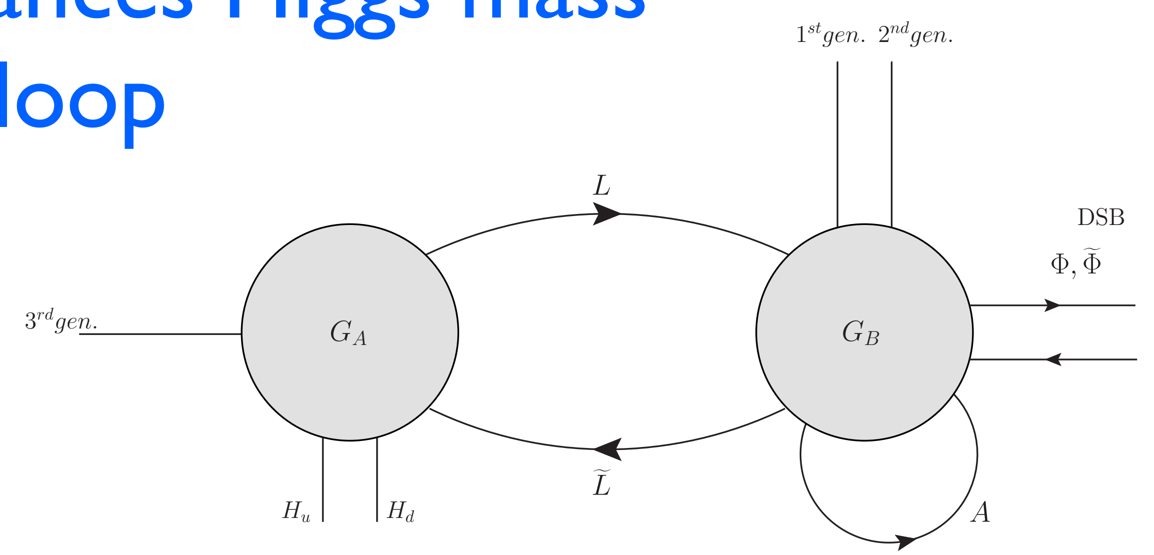
$$m_h^2 \simeq m_z^2 \cos^2(2\beta) + \frac{3}{(4\pi)^2}\frac{m_t^4}{v_{ew}^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2})\right] + \Delta m_{h,1}^2 = \frac{3m_Z^2}{16\pi^2 v_{ew}^2}(1 - \frac{8}{3}\sin\theta_W^2)\cos 2\beta\, m_t^2\, \ln\left(\frac{m_{\tilde{q}_L^3}^2}{m_{\tilde{u}_R^3}}\right)$$





Stop splitting enhances Higgs mass
@ 1-loop

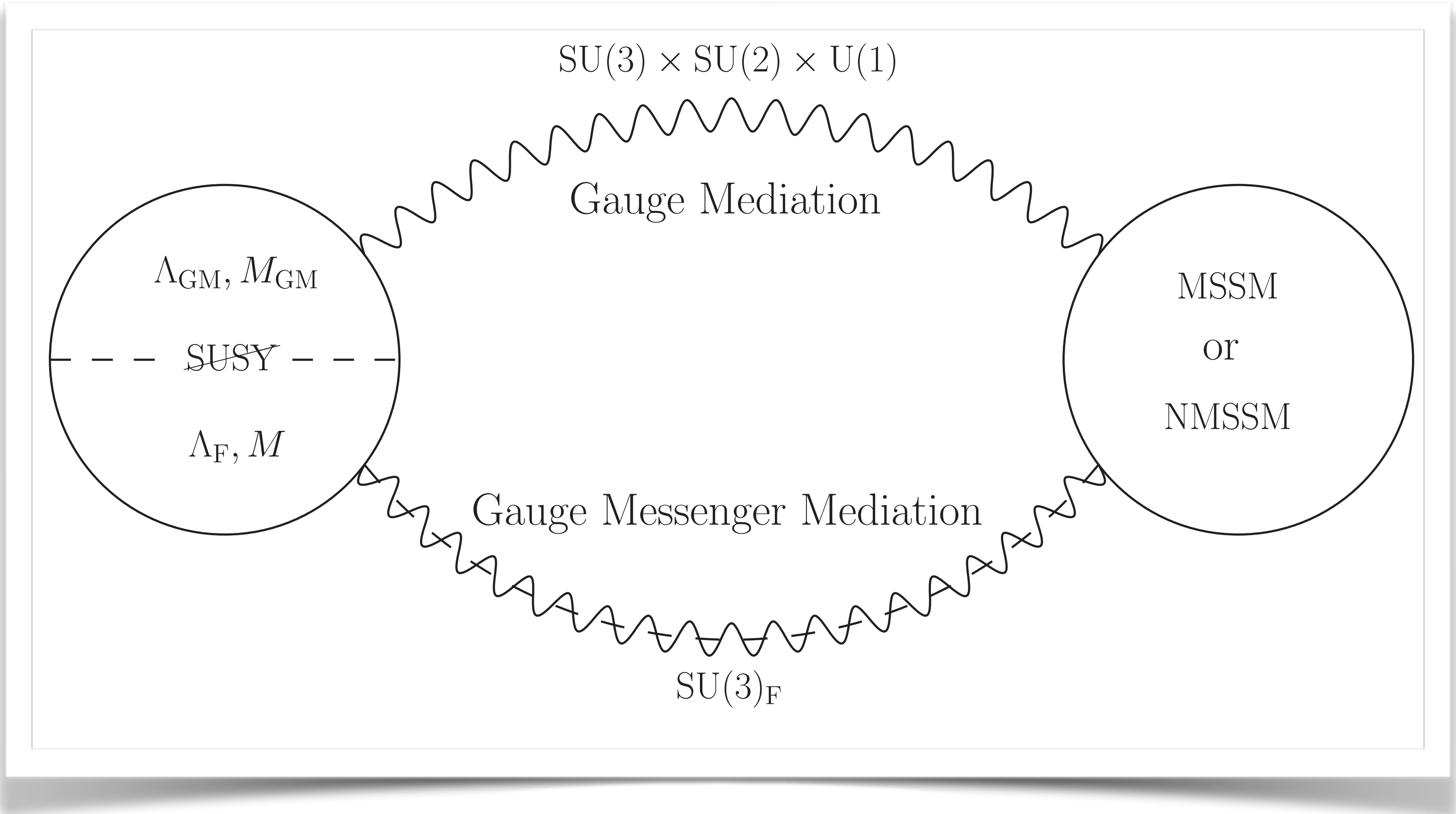




Bharucha, Goudelis, M.M. 1310.4500

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

2. 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

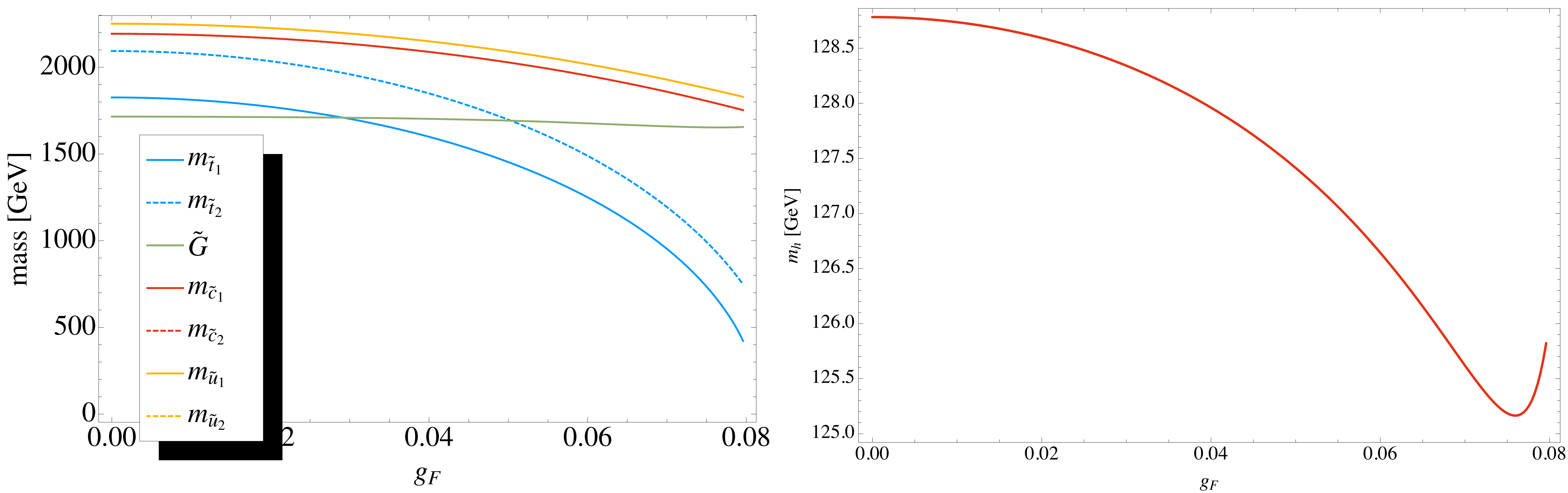
From GMSB

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

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 <u>NMSSM</u> spectrum generator (SPheno)



Squarks and Gluino

Higgs

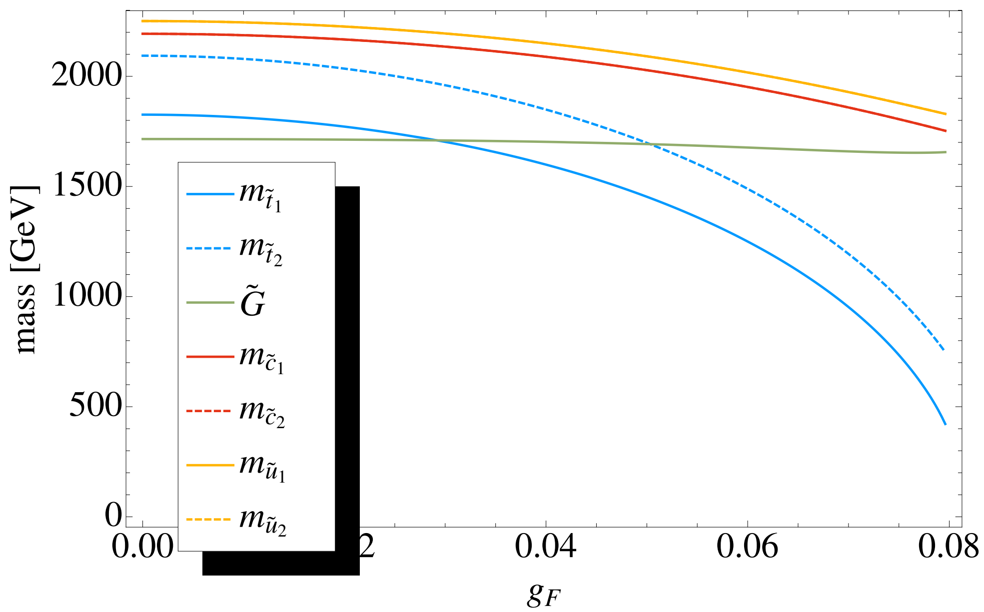
Figure 2. A plot [Left] of the squark and gluino masses for model 1 with the NMSSM. [Right] a plot of Higgs mass versus g_F for the same range. $\lambda = 0.8$, $\kappa = 0.8$, $v_s = 1000$, $m^2_{H_d} = m^2_{H_u} = 10^5$, $\Lambda = \Lambda_F = 2.3 \times 10^5$, $M = 10^7$, $\tan\beta = 1.5$.

Flavour changing neutral currents

(S.Abel & MM) 1404.1318

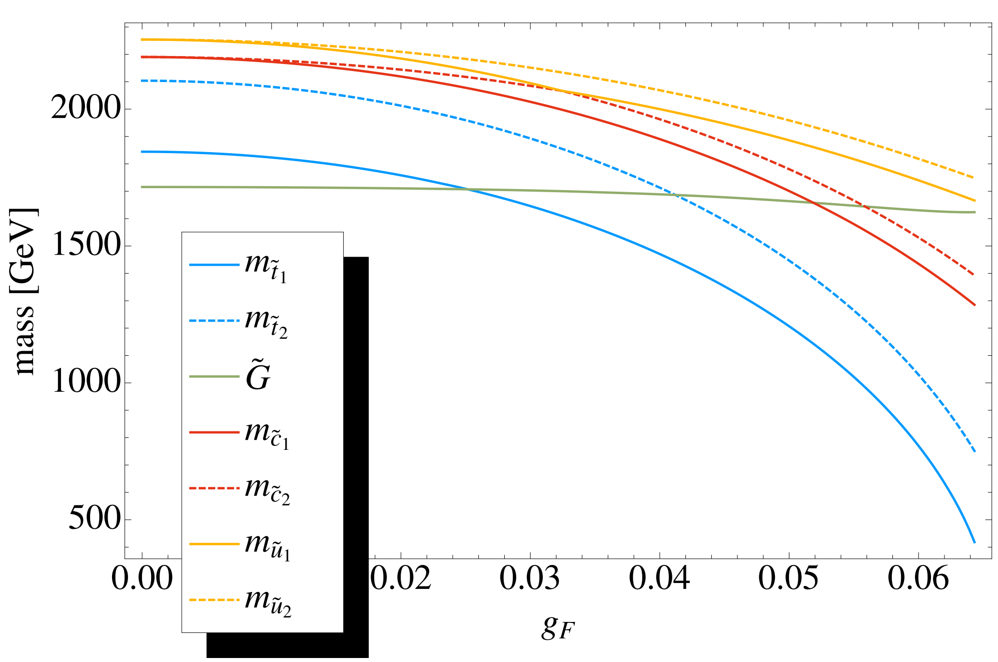
$$\delta_{u,12} < 0.1$$

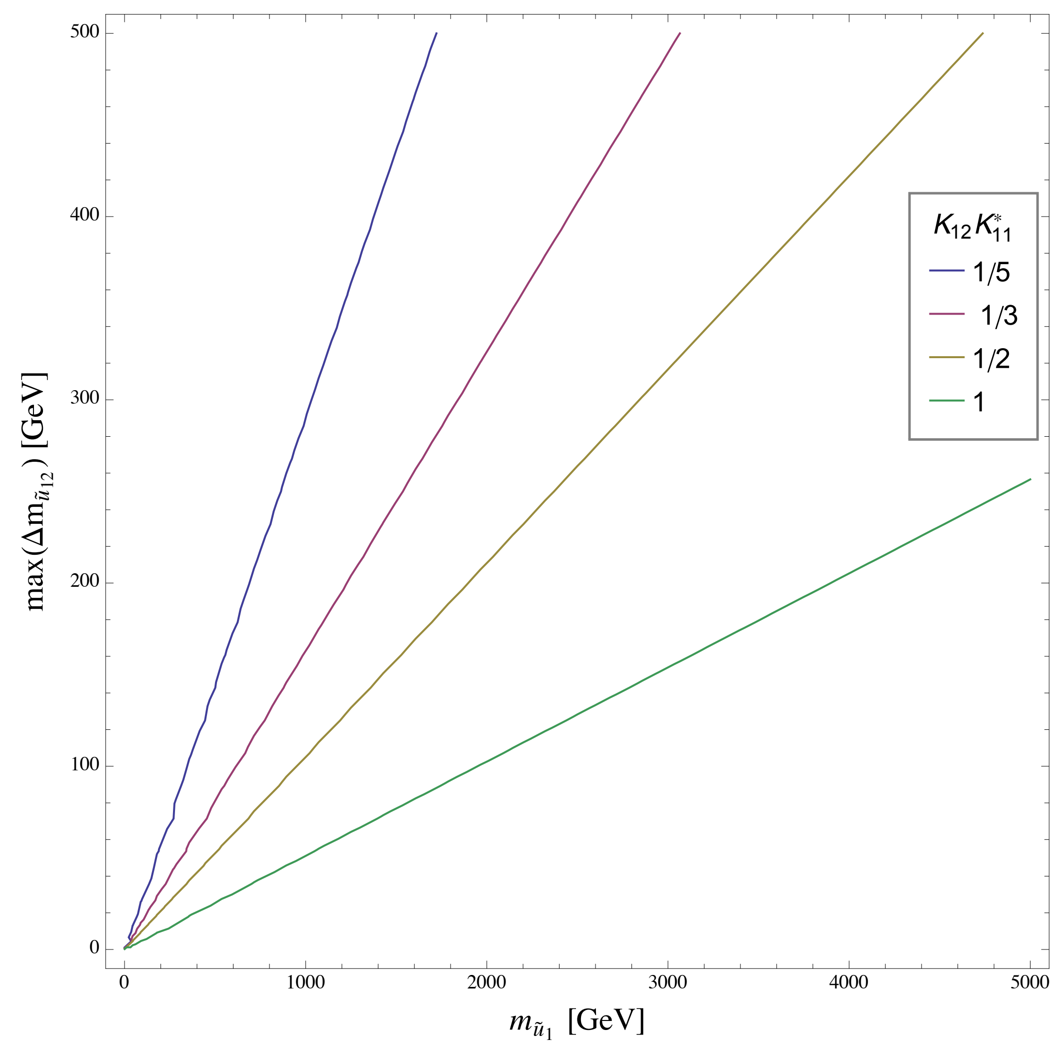
Model 1: degenerate 1st & 2nd



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

Model 2: split 1st & 2nd





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

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

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

Reduces fine tuning on the Higgs.

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

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

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

"Dynamical metastable flavour gauge mediation"

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

$$\mu_{ij} = \begin{pmatrix} \mu & 0 & 0 \\ 0 & \mu & 0 \\ 0 & 0 & \mu_3 \end{pmatrix} \quad \text{and} \quad \varphi^T = \tilde{\varphi} = \begin{pmatrix} \mu \\ \mu \\ 0 \end{pmatrix}$$

$$F_\Phi = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & h\mu_3^2 \end{pmatrix} \quad \text{such that} \quad V_{\rm min} = |h^2 \mu_3^4| ,$$

Natural SUSY is more generic in the string landscape than previously thought!

$$\delta m^2_{Q,U,D} = -\frac{g_F^2}{16\pi^2} \frac{|h^2 \mu_3^4|}{\mu^2} \begin{pmatrix} \frac{8}{9} & 0 & 0 \\ 0 & \frac{8}{9} & 0 \\ 0 & 0 & \frac{20}{9} \end{pmatrix}$$

Perhaps we can explain Yukawas too!

(S.Abel & MM) 1404.1318

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

Available for hire :)

Thanks for listening!

Conclusions

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