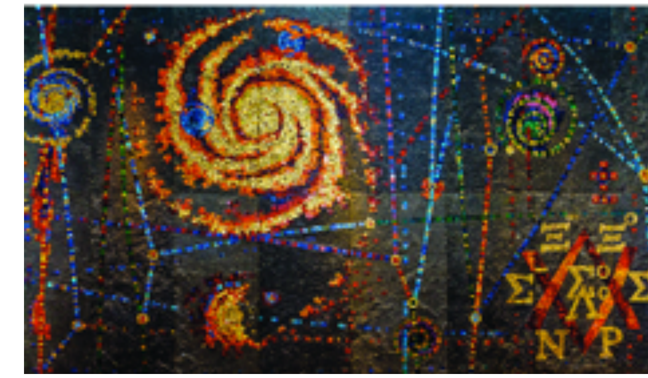
21 - 26 JULY 2014, MANCHESTER, ENGLAND
SUSY2014
THE 22ND INTERNATIONAL CONFERENCE ON SUPERSYMMETRY AND UNIFICATION OF FUNDAMENTAL INTERACTIONS



Confronting Higgs couplings from D-term Extensions & Natural SUSY at the ILC

Moritz McGarrie
with
G.Moortgat-Pick (DESY,Hamburg) & S.Porto (Hamburg)
and
A.Bharucha(Marseille) & A.Goudelis(LAPTh) ArXiv:1310:4500

FACULTY OF PHYSICS WARSAW UNIVERSITY

UNIVERSITY OF THE WITWATERSRAND JOHANNESBURG

UNIVERSITAS VARSOVIENSIS

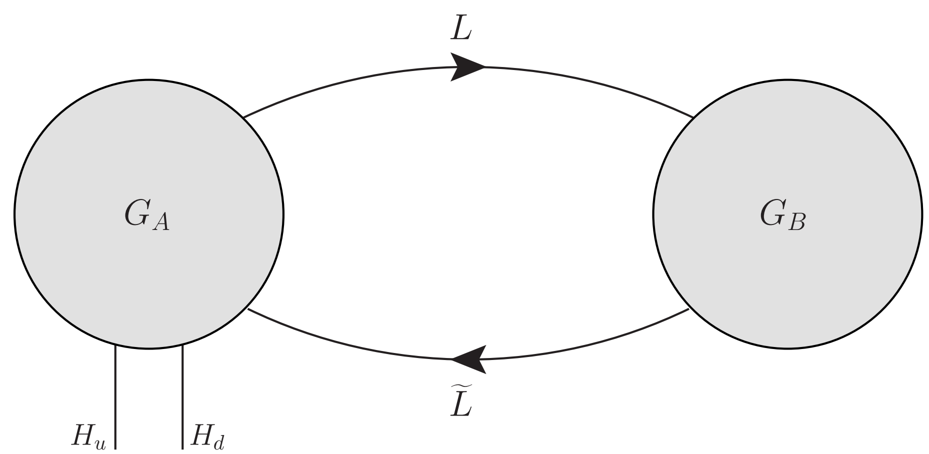
Non decoupled D-terms

UV

↓

IR

at low energies
MSSM +



- Two gauge groups
- Two D-term scalar potentials
- Higgs only charged under one
- Integrate out Linking fields
- An effective action remains
- Works for U(1)_Y & SU(2)_L

$$V = V_{D_A} + V_{D_B} + \dots$$

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

$U(1)_A \times U(1)_B \to U(1)_Y$

$SU(2)_A \times SU(2)_B \to SU(2)_L$

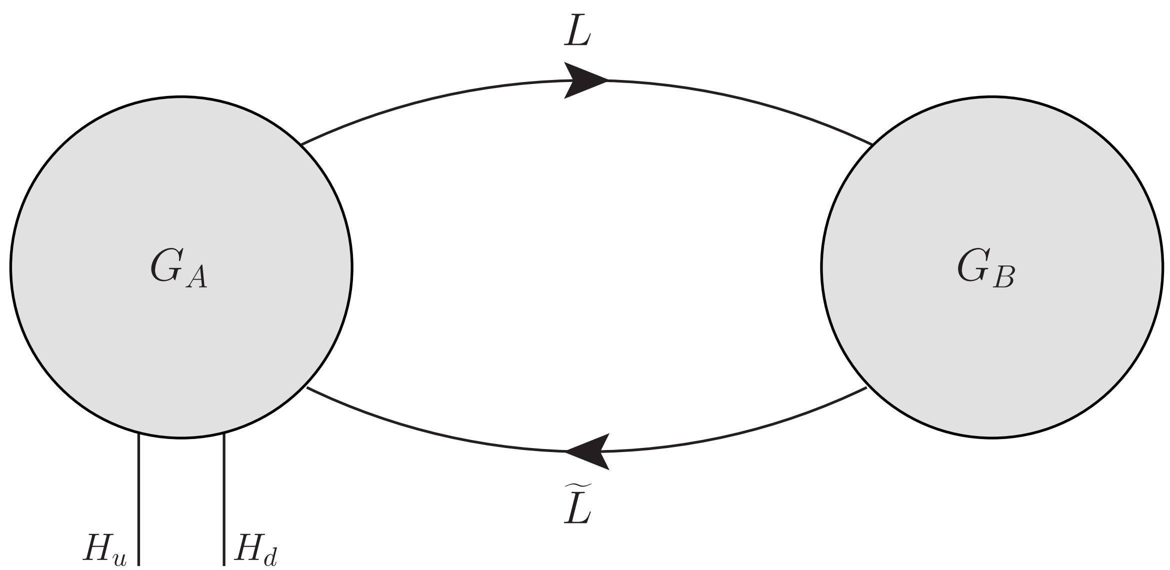
$$m_h^2 \simeq m_z^2\cos^2(2\beta) + \frac{3}{(4\pi)^2}\frac{m_t^4}{v_{ew}^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}(1 - \frac{X_t^2}{12m_{\tilde{t}}^2})\right]$$

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

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

Lifts the Higgs mass at tree level

Non decoupled D-terms



Related works:

- Csaki, Erlich, Grojean,Kribs 0106044
- Batra, Delgado, Kaplan, Tait 0309149/0404251/0409073
- Medina, Shah, Wagner 0904.1625
- M.M. 1009.0012/1101.5158
- Auzzi, Giveon, Gudnason, Shacham 1009.1714/1011.1664
- Huo, Lee, Thalapillil, Wagner 1212:0560
- Craig, Katz 1212.2635
- Bharucha,Goudelis, M.M. 1310.4500
- and more ……

Features:

✓ Lifts the Higgs at tree level

✓ Allows for light stops

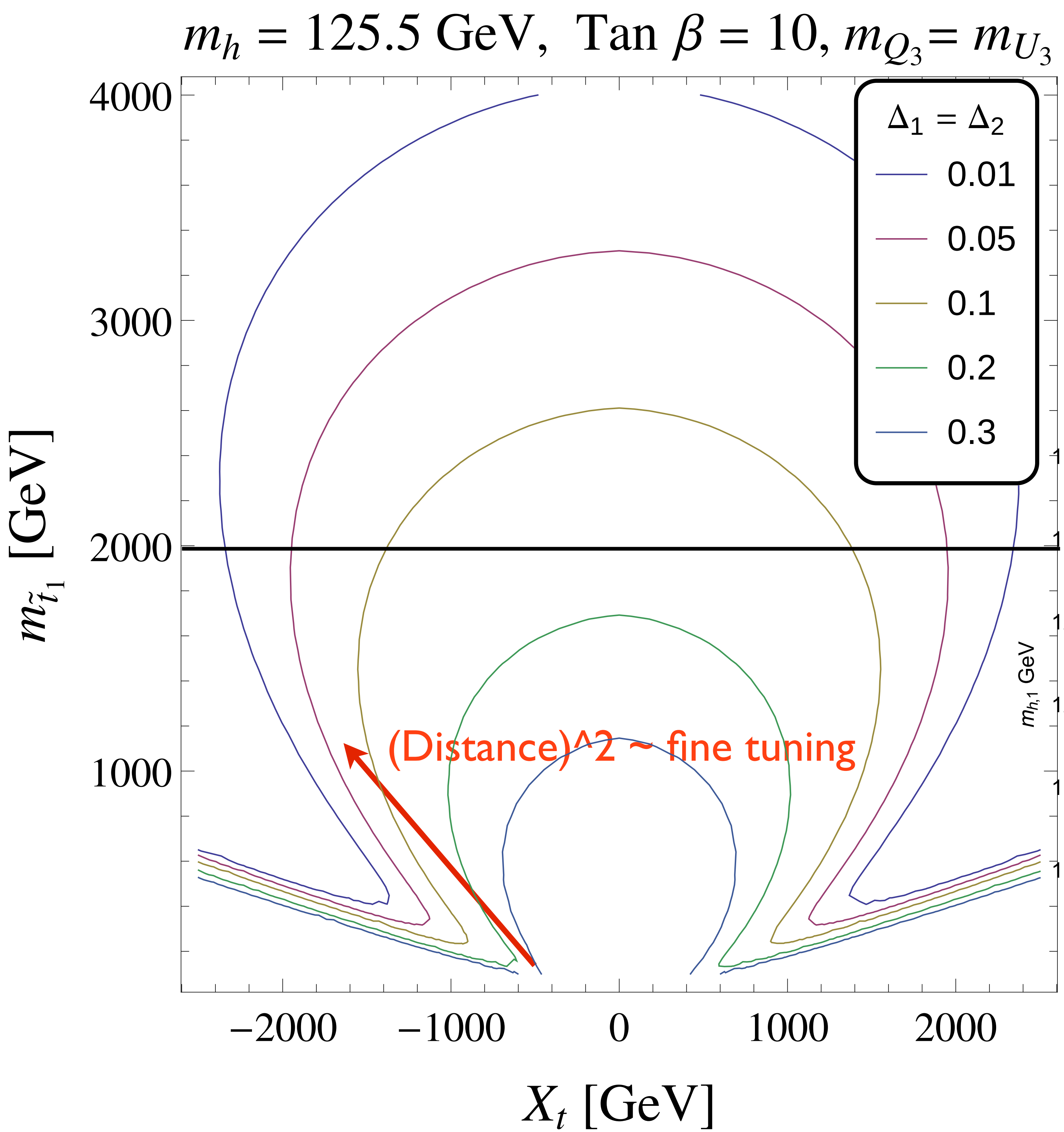
✓ More natural than NMSSM?

✓ embeds into magnetic SQCD

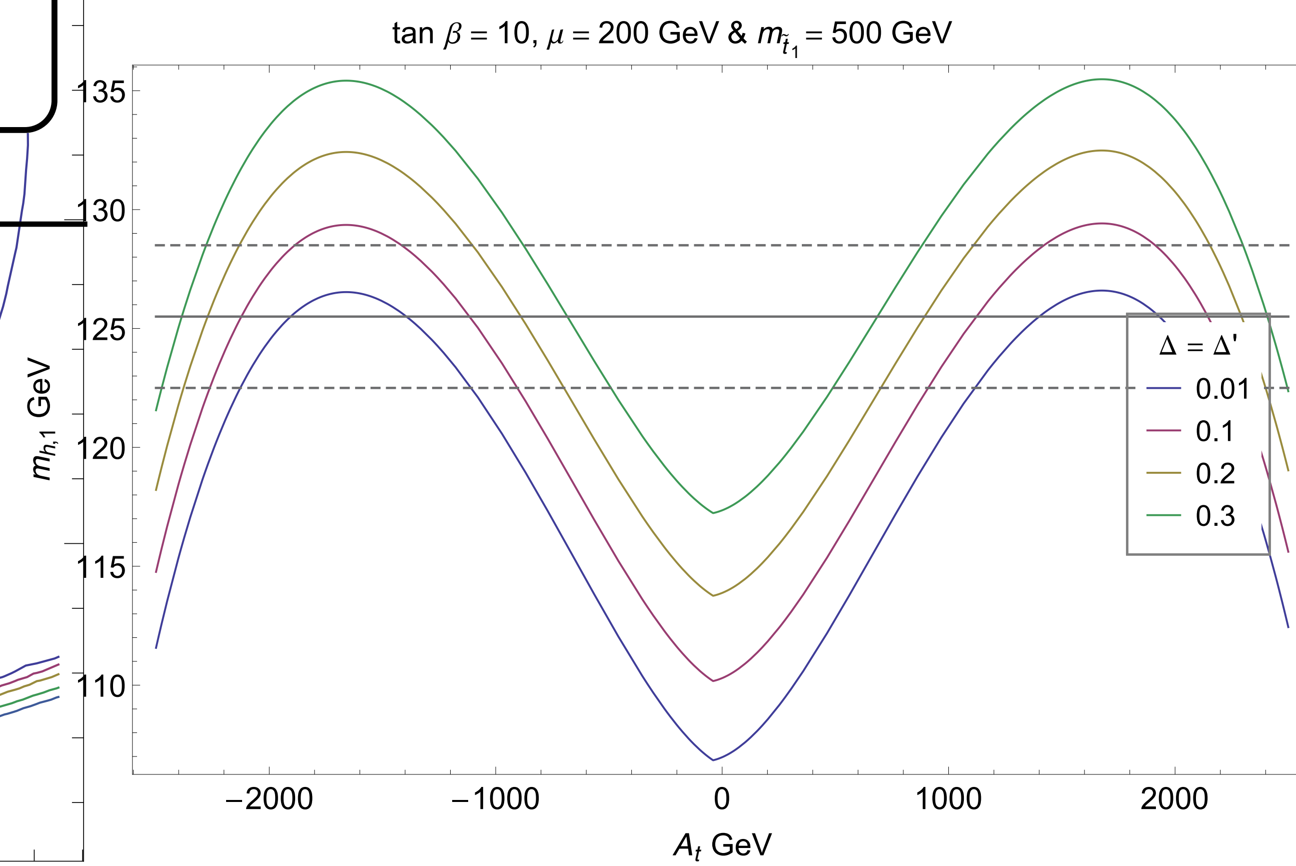
✓ Deconstructs an extra dimension

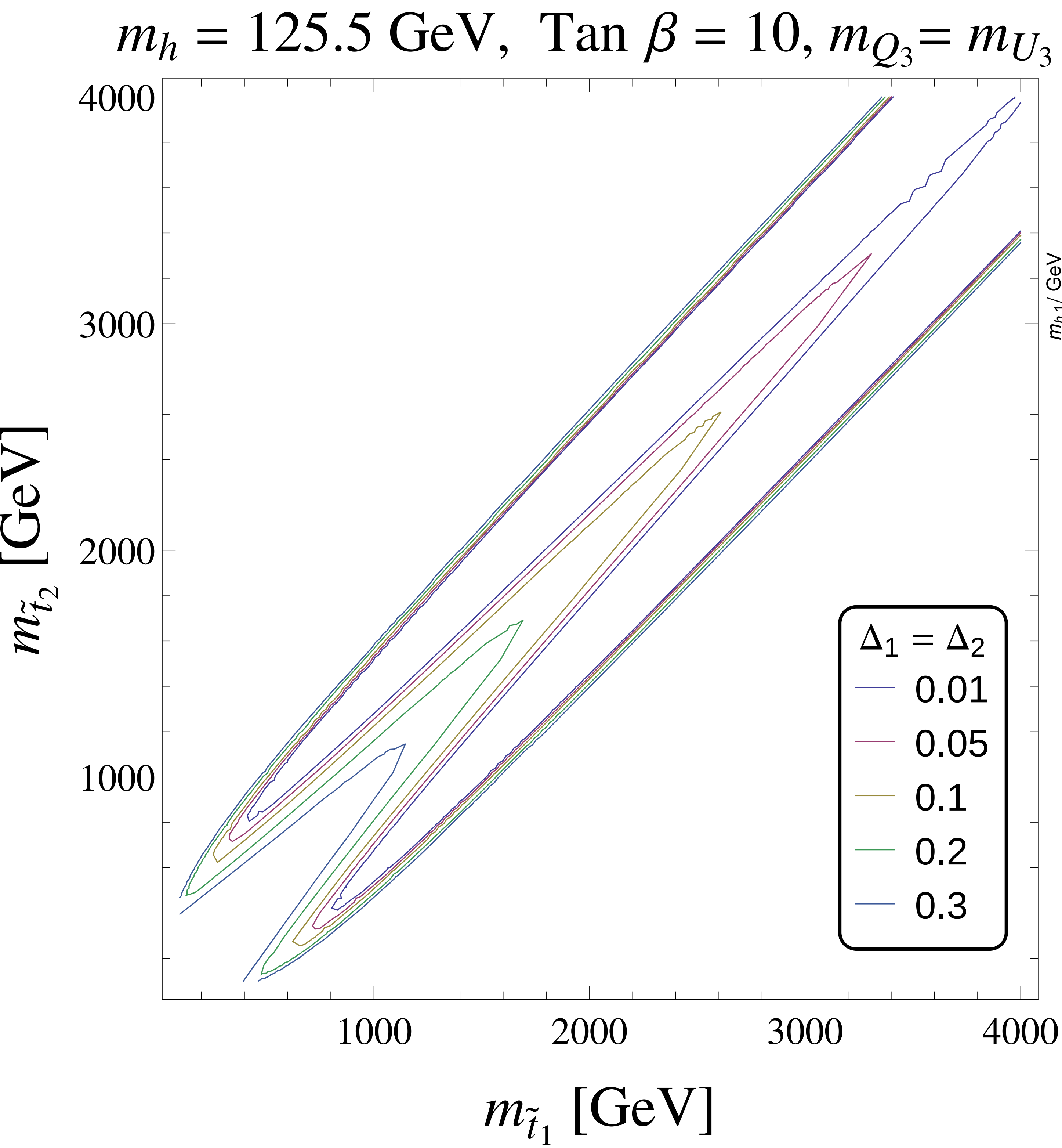
✓ "Split families": Batra, Kaplan, Tait, Delgado

0404251/0409073

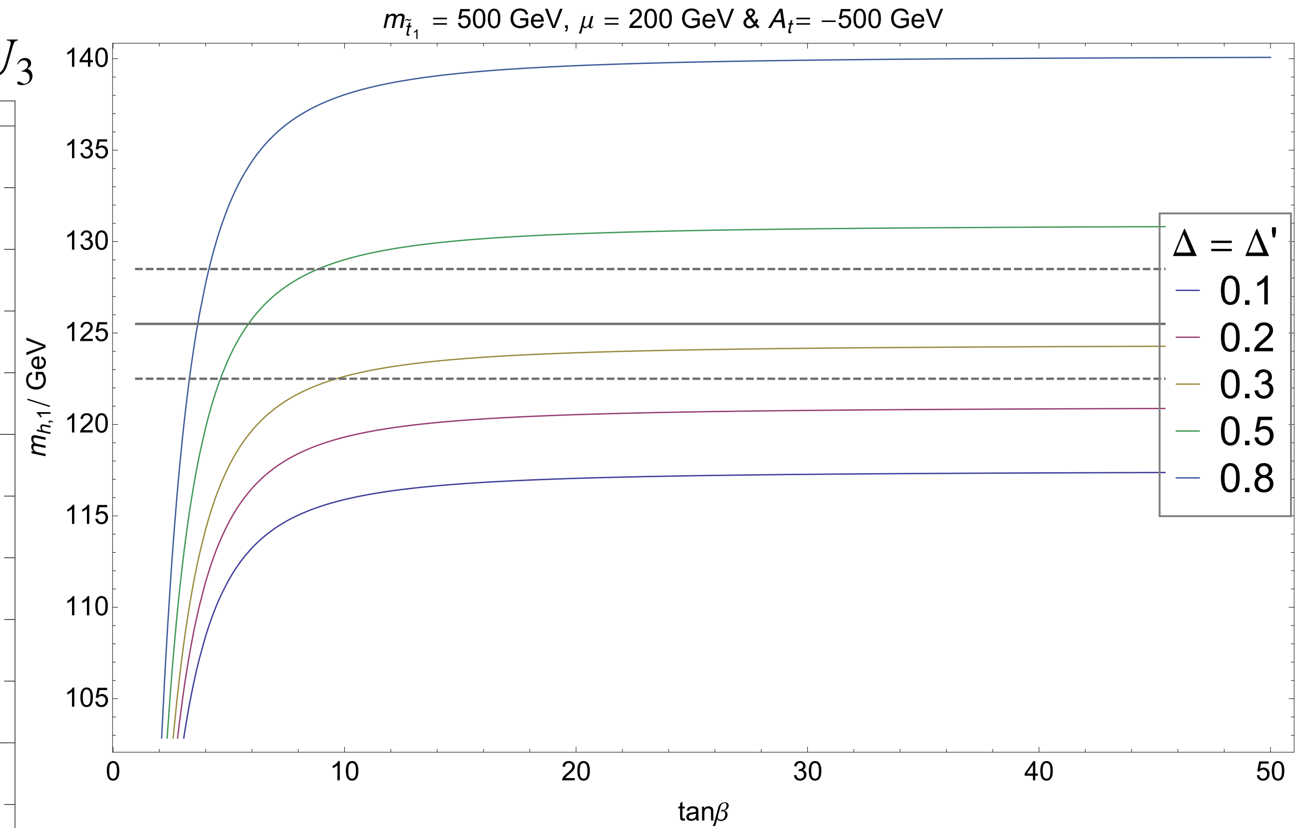


Sub 2 TeV stops for $\Delta \geq 0.1$

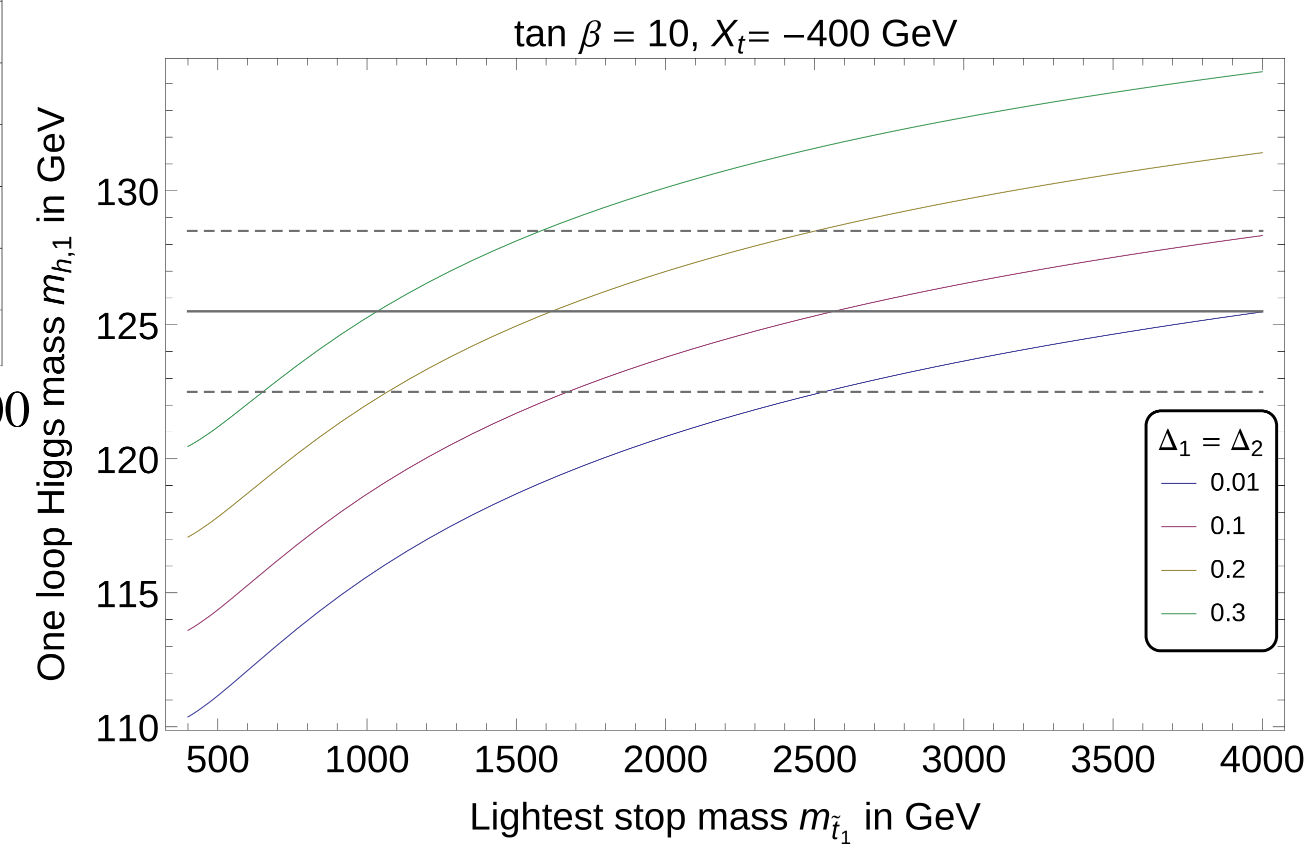




The contribution from maximal mixing
can be lowered

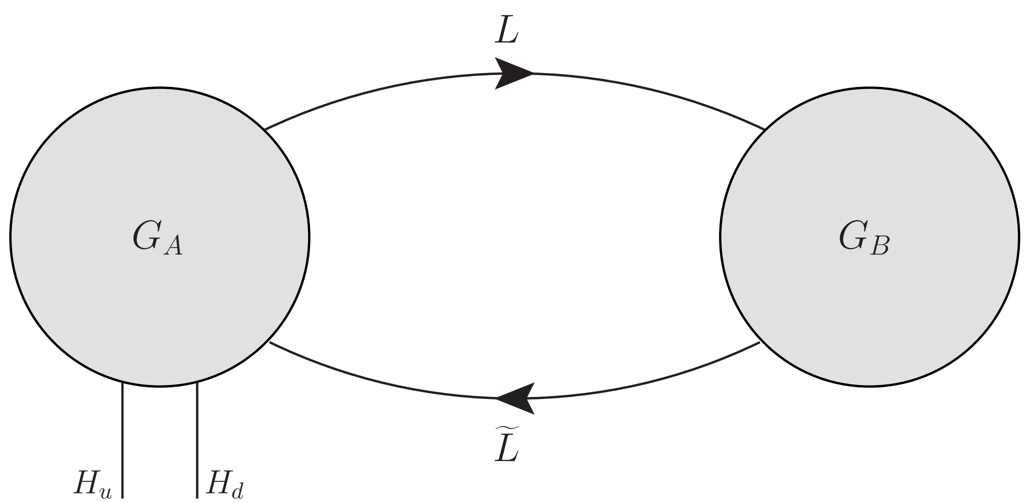


•D-term enhancement for ALL tanbeta

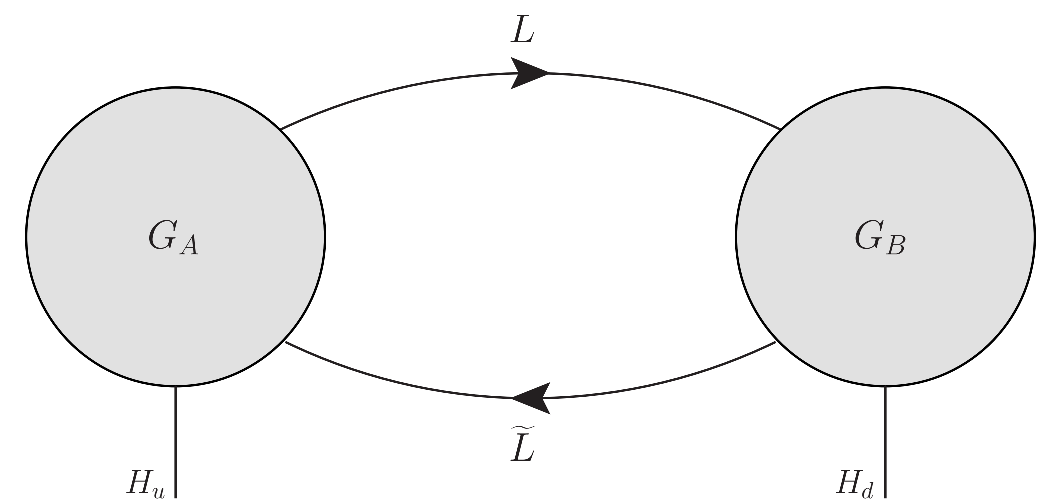


There are two types

Vector-like



Chiral type

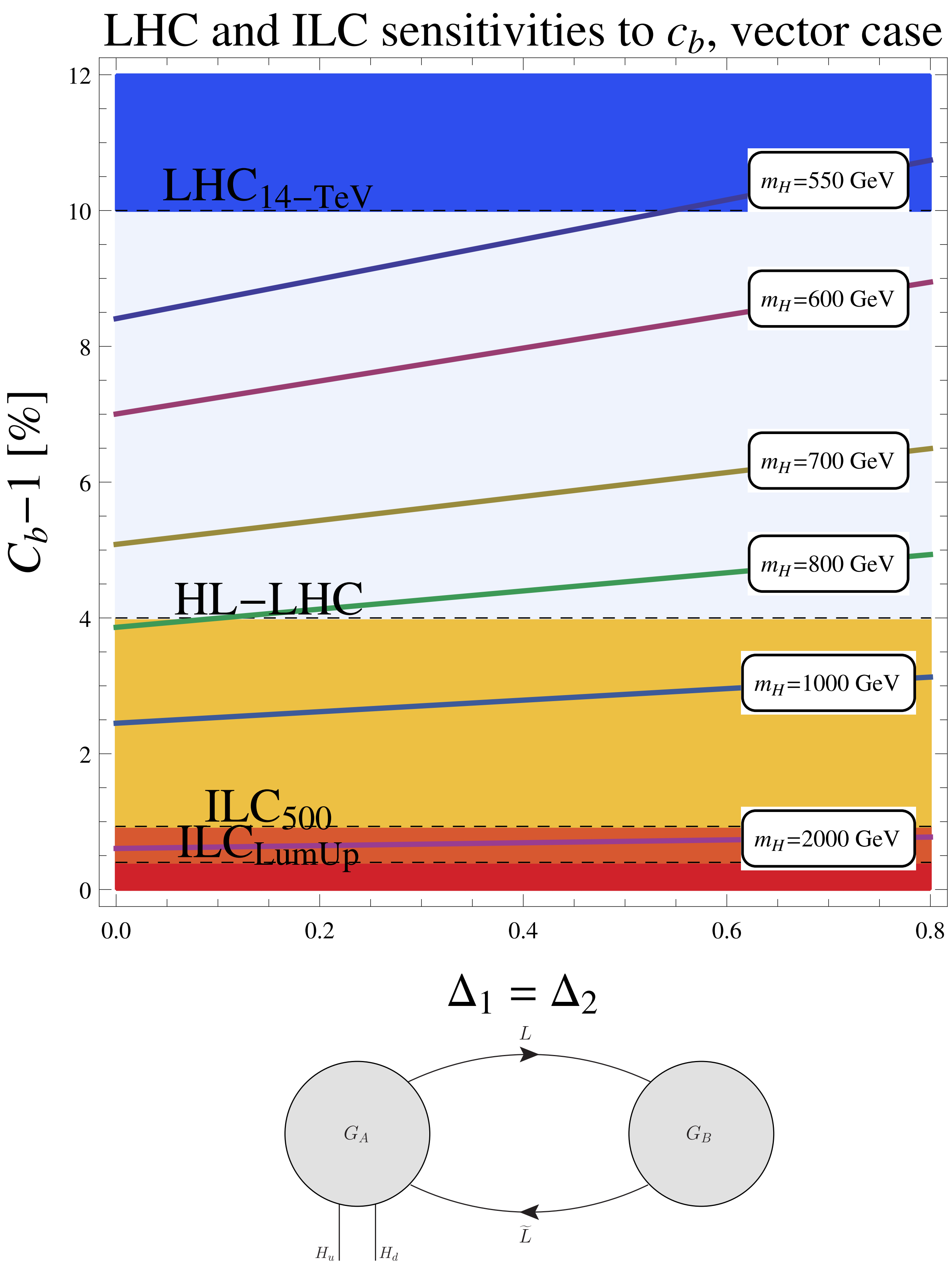


- Similar effect on Higgs mass
- Different effect on Higgs branching ratios
- Testable at the ILC

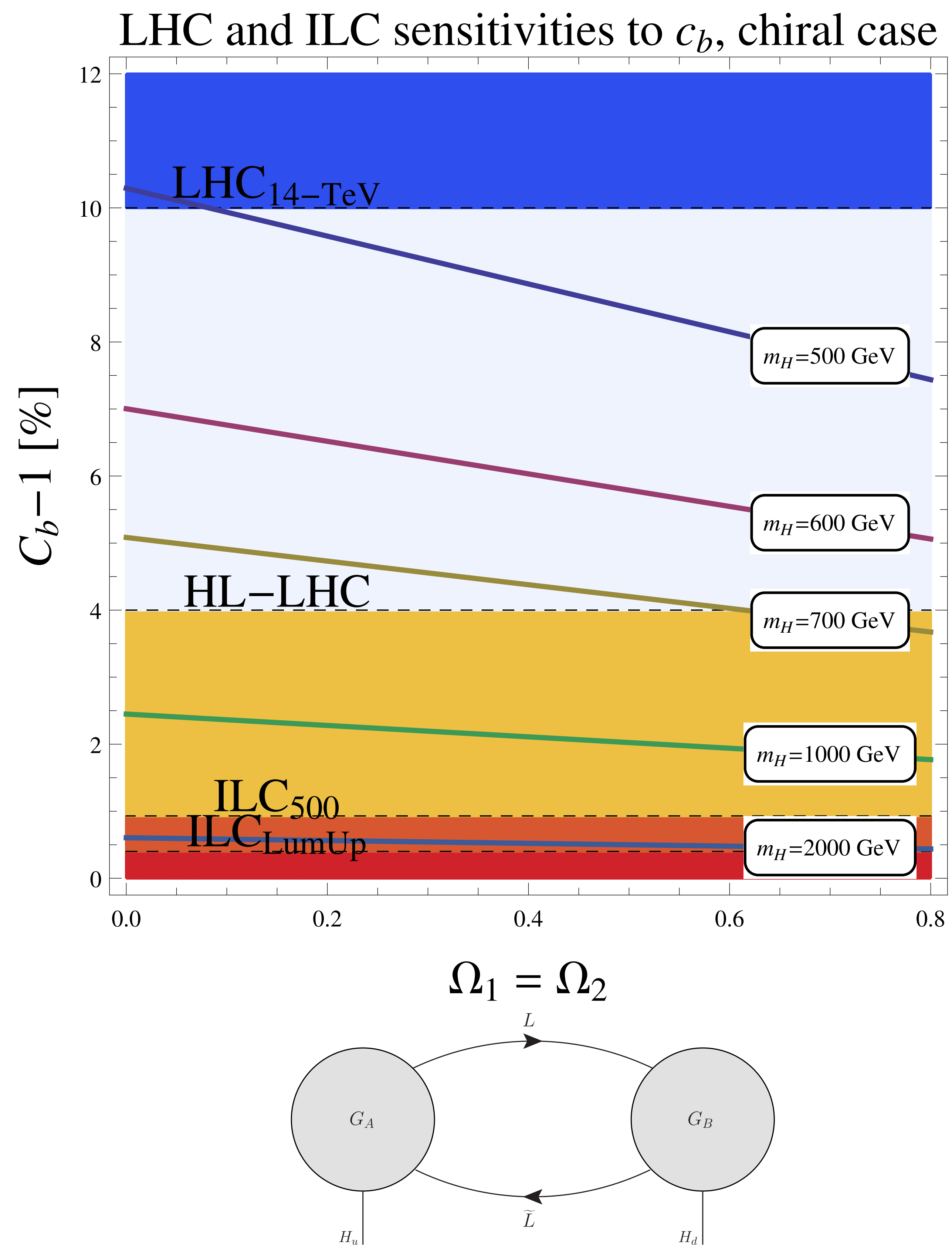
$$c_b^{\text{vector}} \simeq \left(1 - \frac{m_h^2}{m_H^2}\right)^{-1} \left(1 + \frac{[g_2^2(1+\Delta_2) + \frac{3}{5}g_1^2(1+\Delta_1)]v^2}{4m_H^2}\right)$$

$$c_b^{\text{chiral}} \simeq \left(1 - \frac{m_h^2}{m_H^2}\right)^{-1} \left(1 + \frac{[g_2^2(1-\Omega_2) + \frac{3}{5}g_1^2(1-\Omega_1)]v^2}{4m_H^2}\right)$$

Vector-like

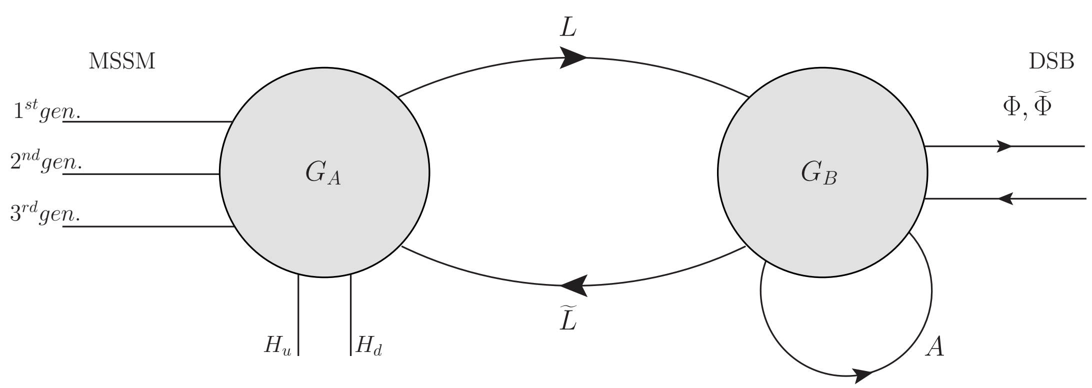


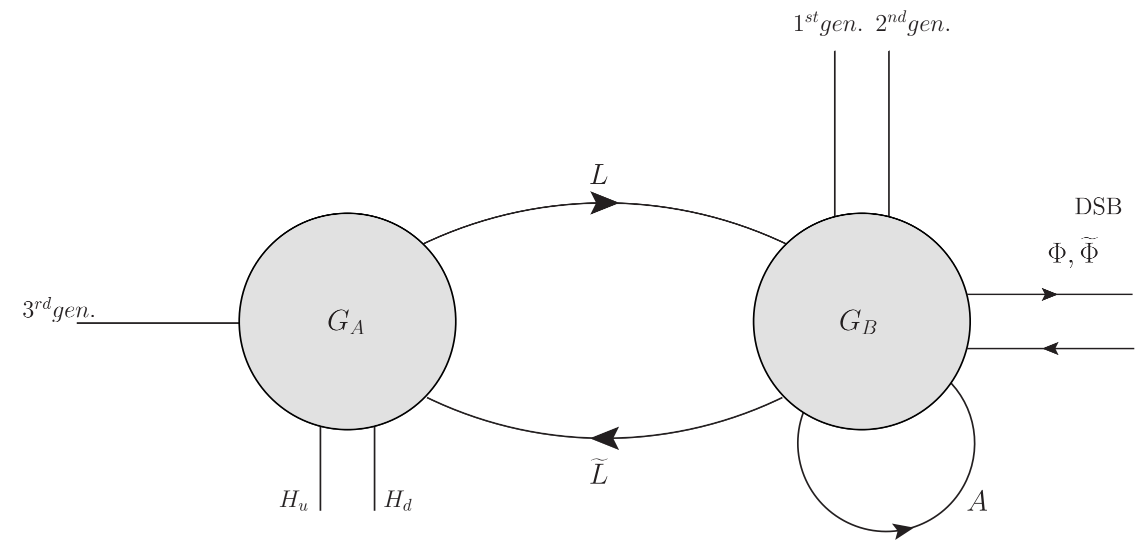
Chiral type

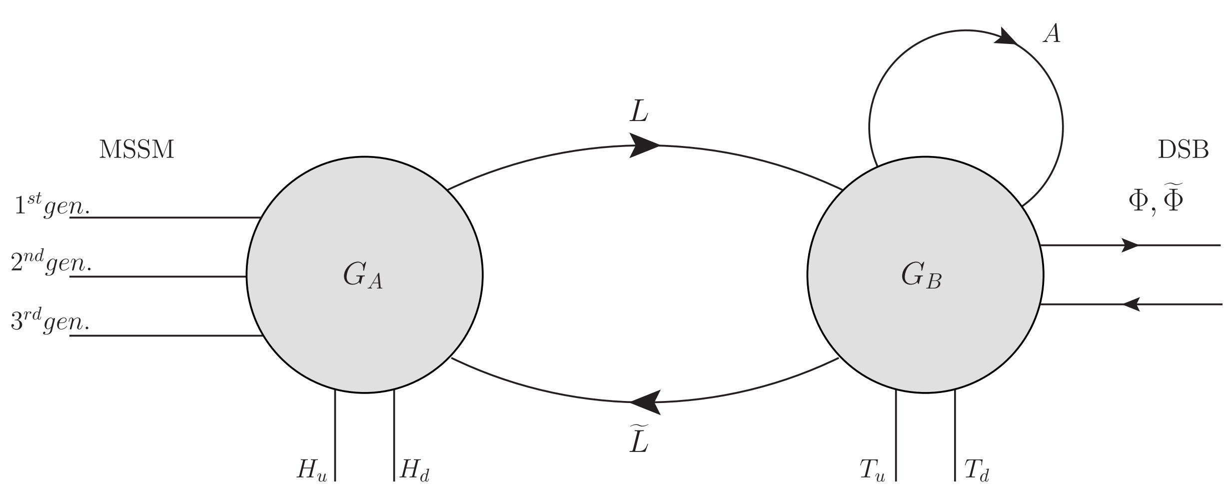


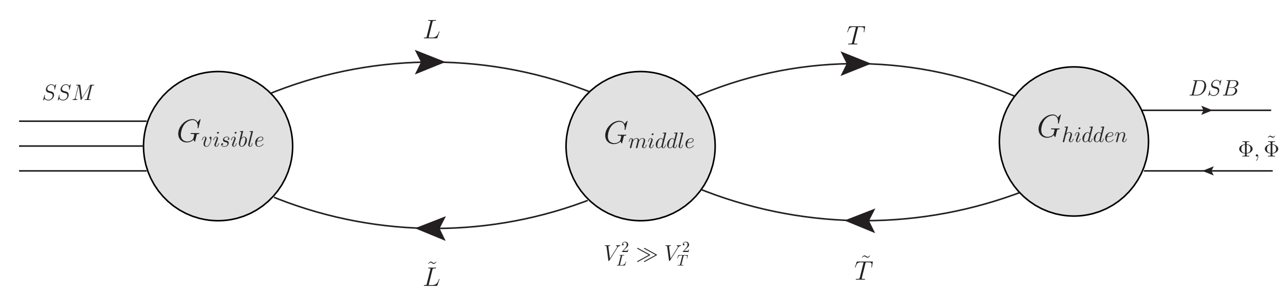
The Quiver Variations

as UV completions







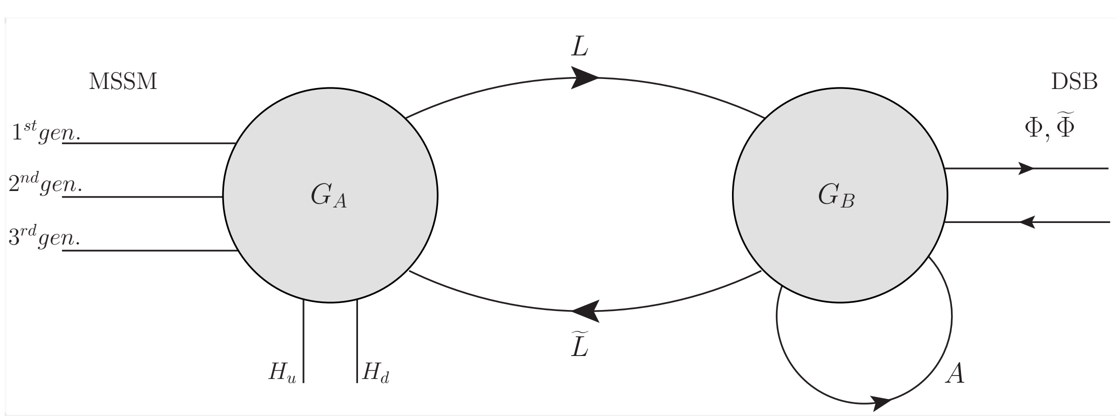


A *meta* model

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	$(\frac{1}{6}, 1, 3, 0, 2)$	-1
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, 1, 1, 0, 2)$	-1
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, 1, 1, 0, 2)$	$+1$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, 1, 1, 0, 2)$	$+1$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3}, 1, \overline{3}, 0, 1)$	-1
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, 1, \overline{3}, 0, 1)$	-1
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, 1, 1, 0, 1)$	-1
$\hat{L}$	L	ψ_L	1	$(-\frac{1}{2}, \overline{2}, 1, \frac{1}{2}, 2)$	$+1$
$\hat{\tilde{L}}$	$\tilde{L}$	$\psi_{\tilde{L}}$	1	$(\frac{1}{2}, 2, 1, -\frac{1}{2}, \overline{2})$	$+1$
$\hat{K}$	K	ψ_K	1	$(0, 1, 1, 0, 1)$	$+1$
$\hat{A}$	A	ψ_A	1	$(0, 3, 1, 0, 1)$	$+1$

Table 2. Matter fields of the model.



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

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

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?

Bharucha, Goudelis, M.M. 1310.4500

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

↓

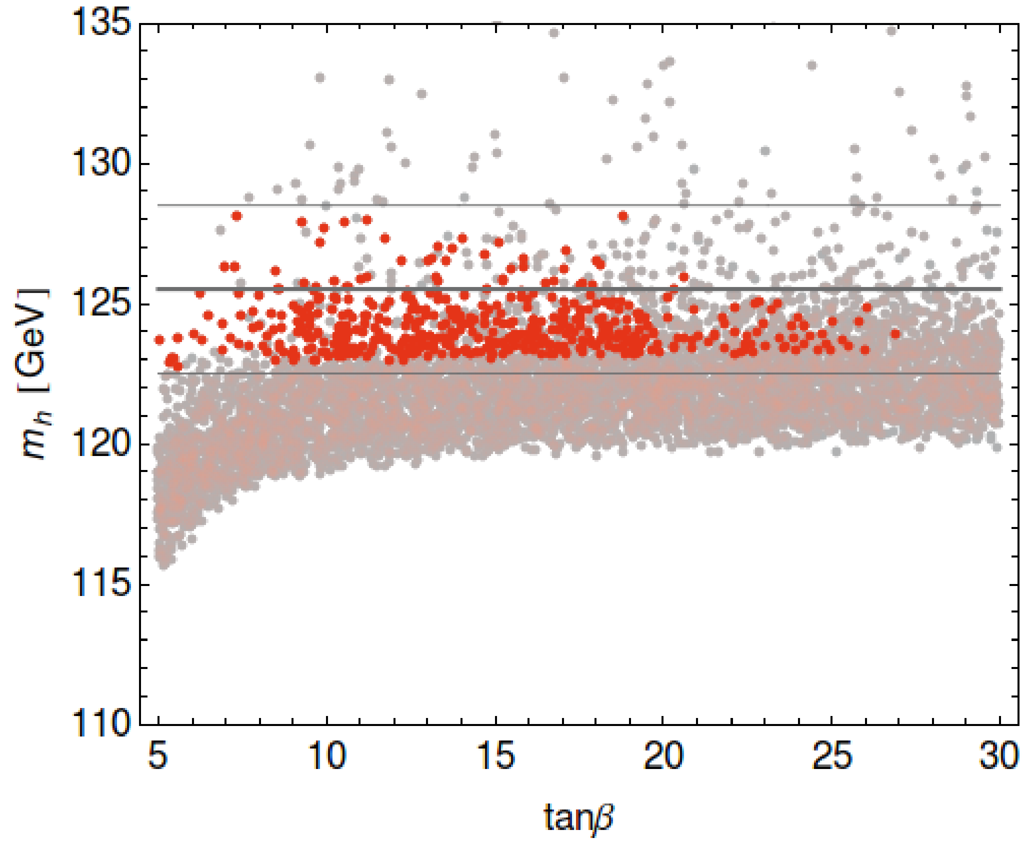
Threshold scale: MSSM

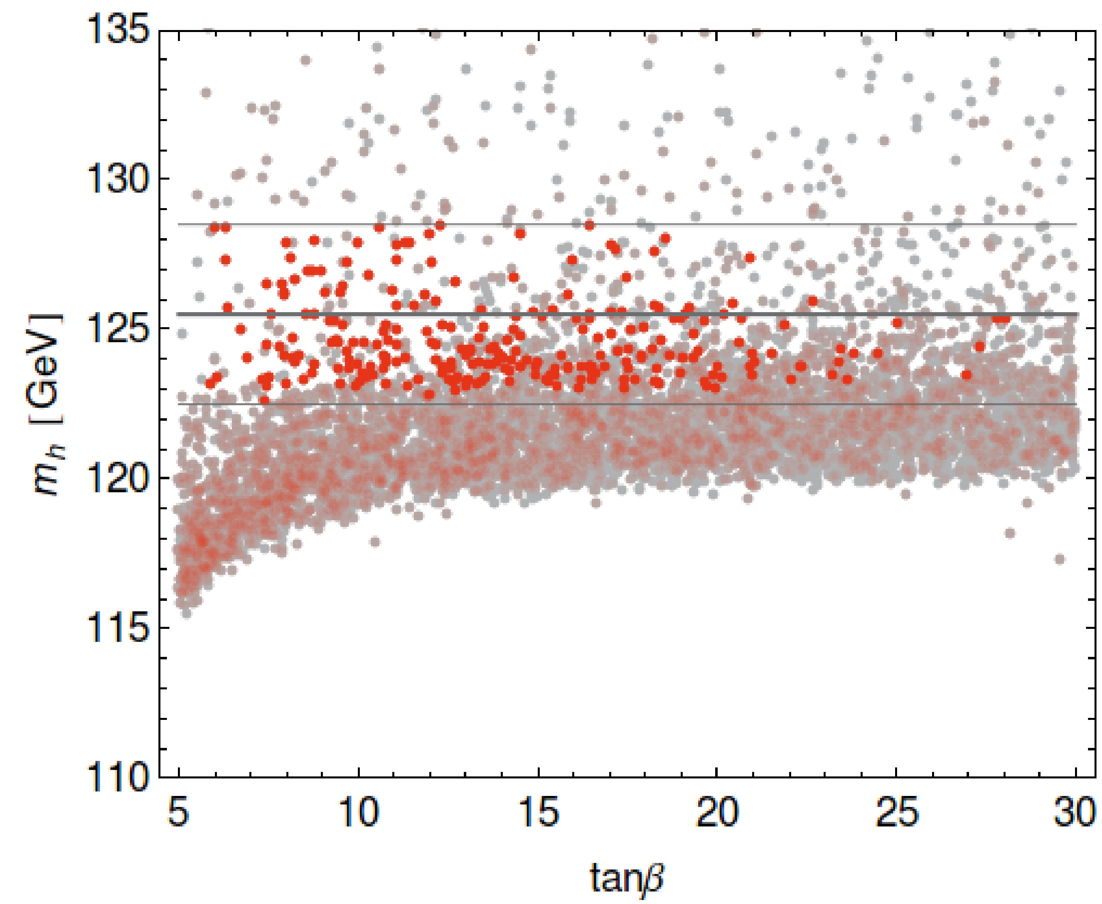
↓

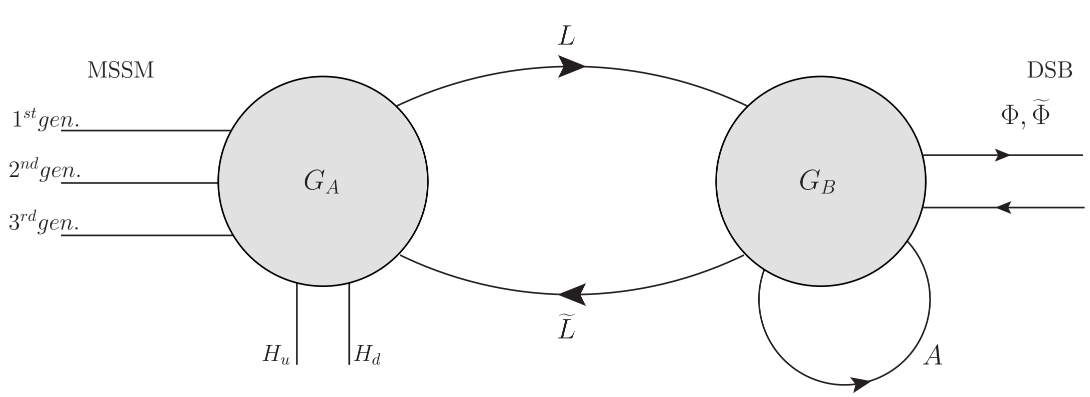
LHC

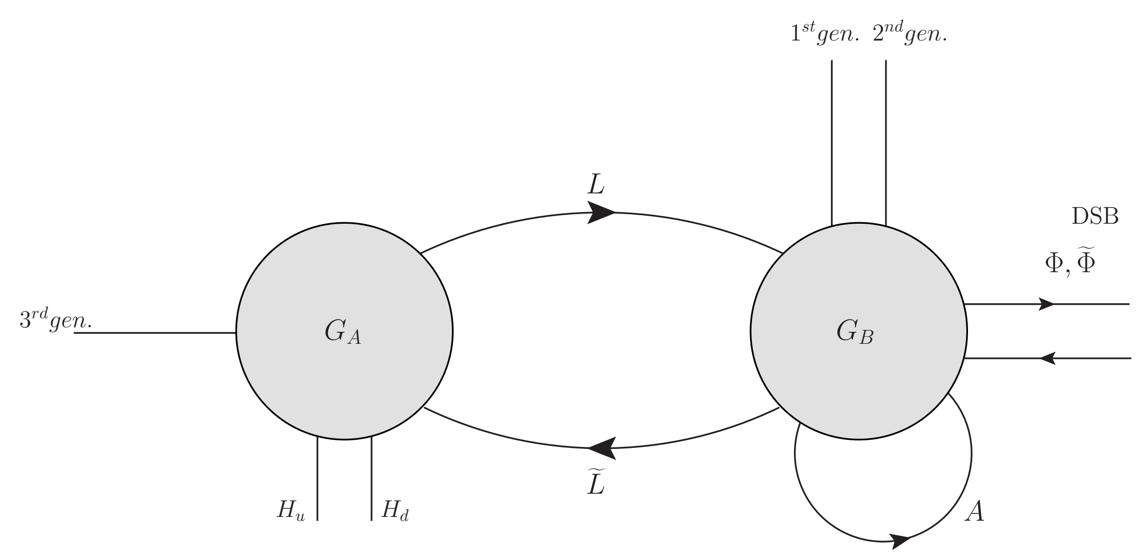
Same precision as SOFTSUSY, SPheno, SUSPECT

Bharucha,Goudelis, M.M. 1310.4500

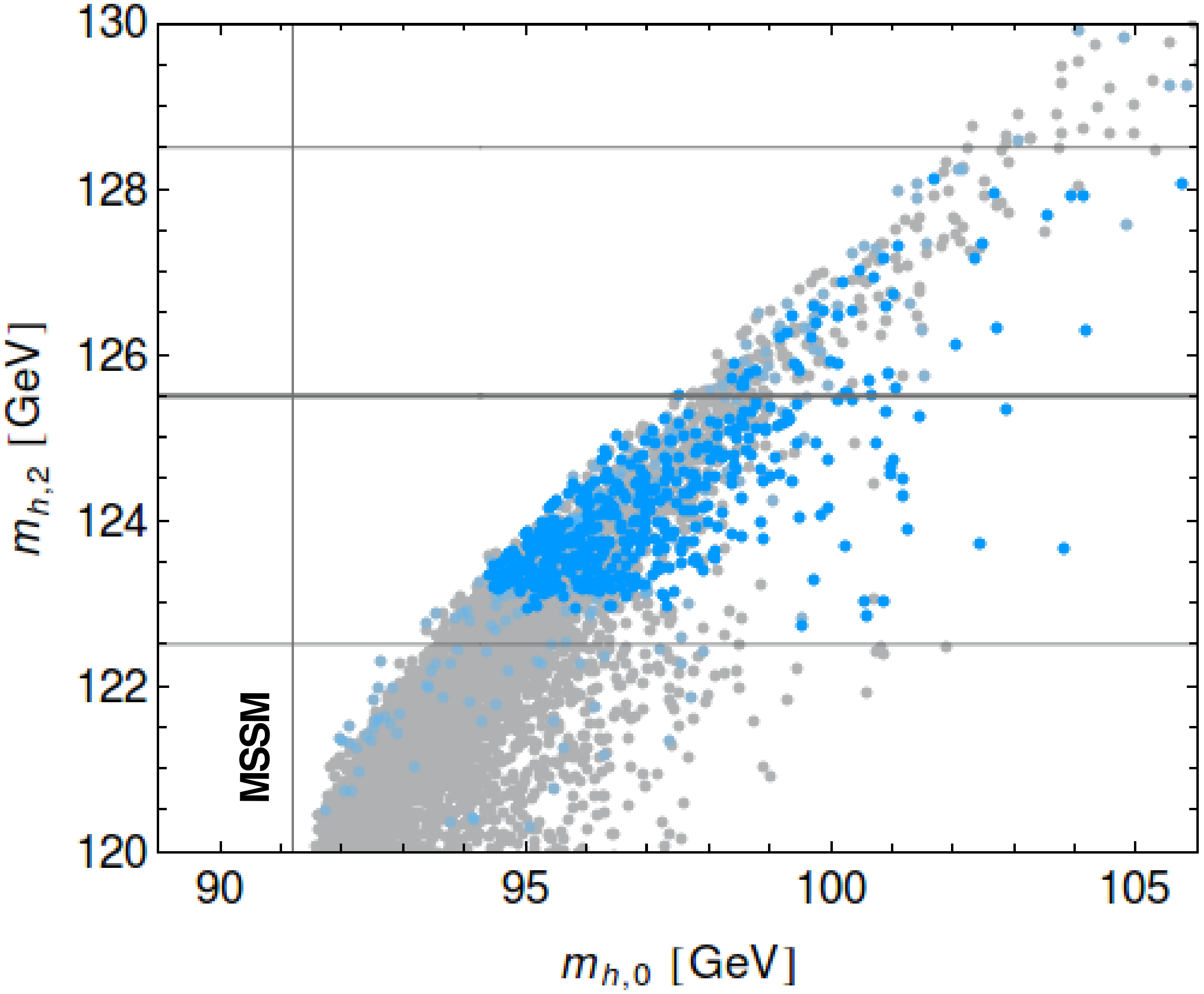


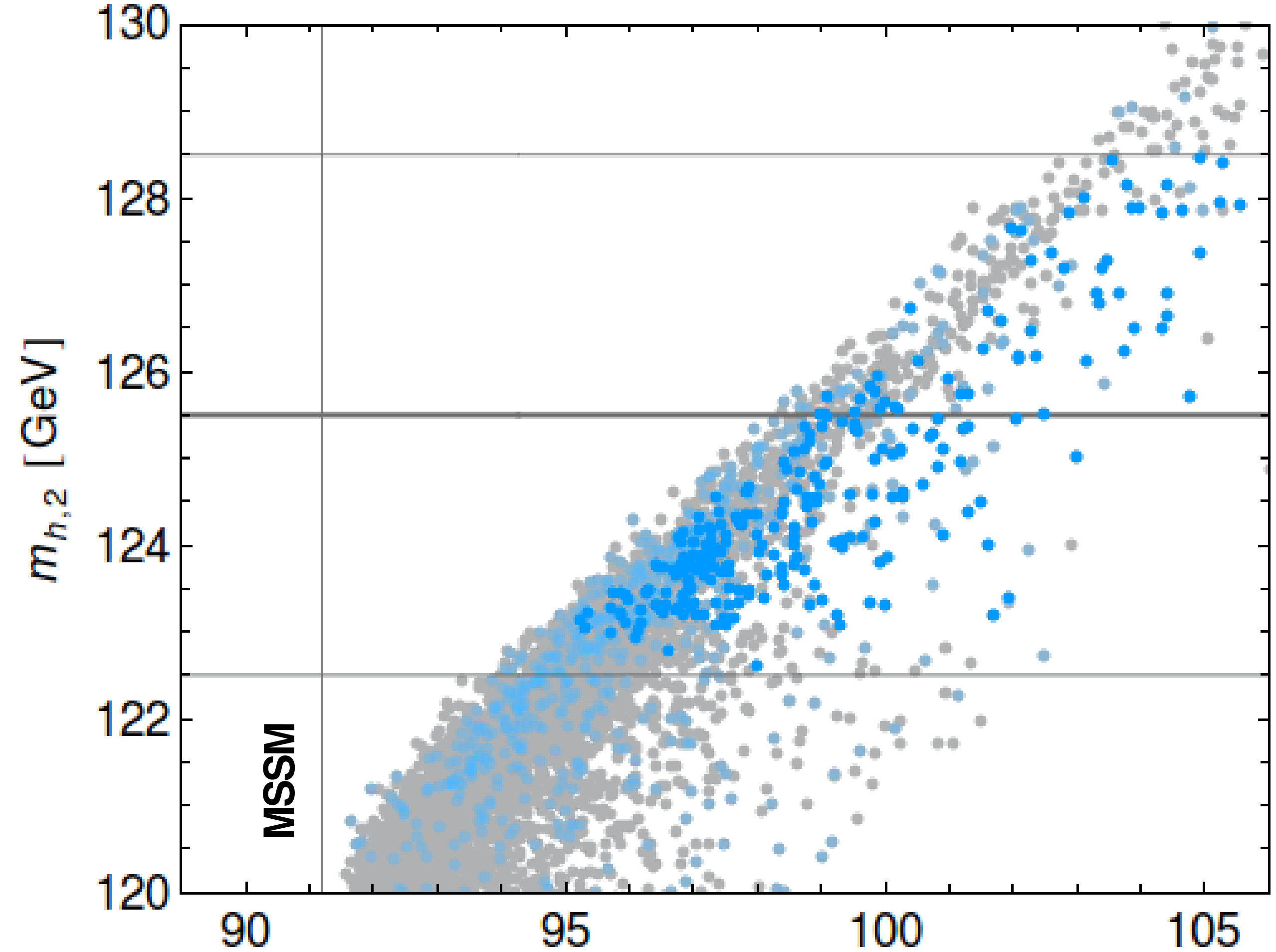


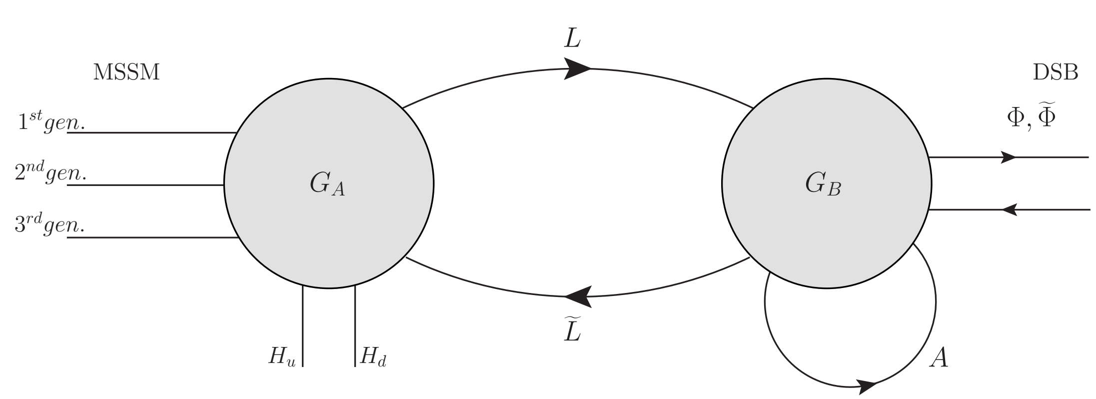


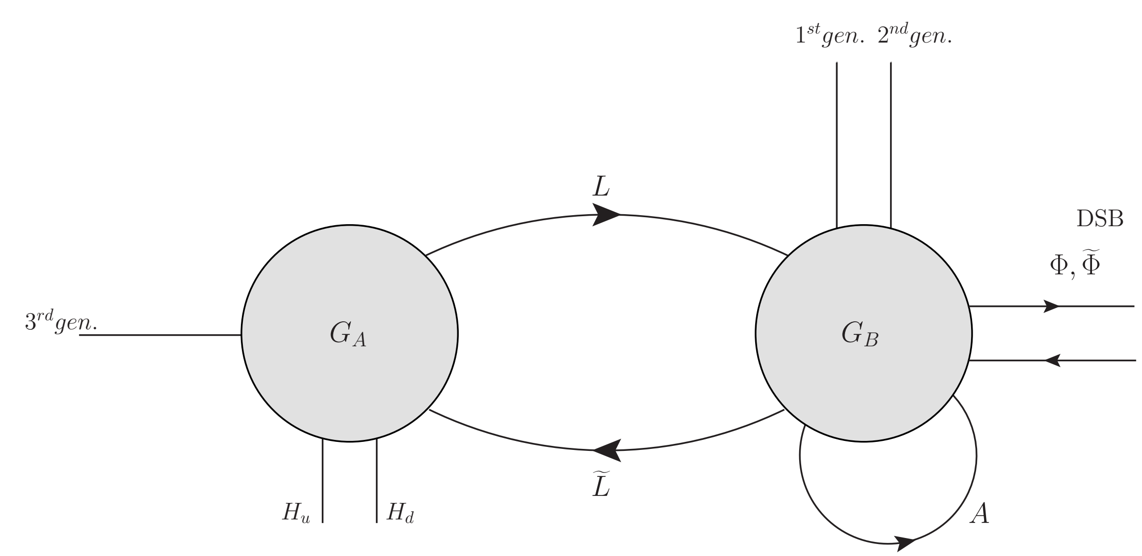


Bharucha,Goudelis, M.M. 1310.4500

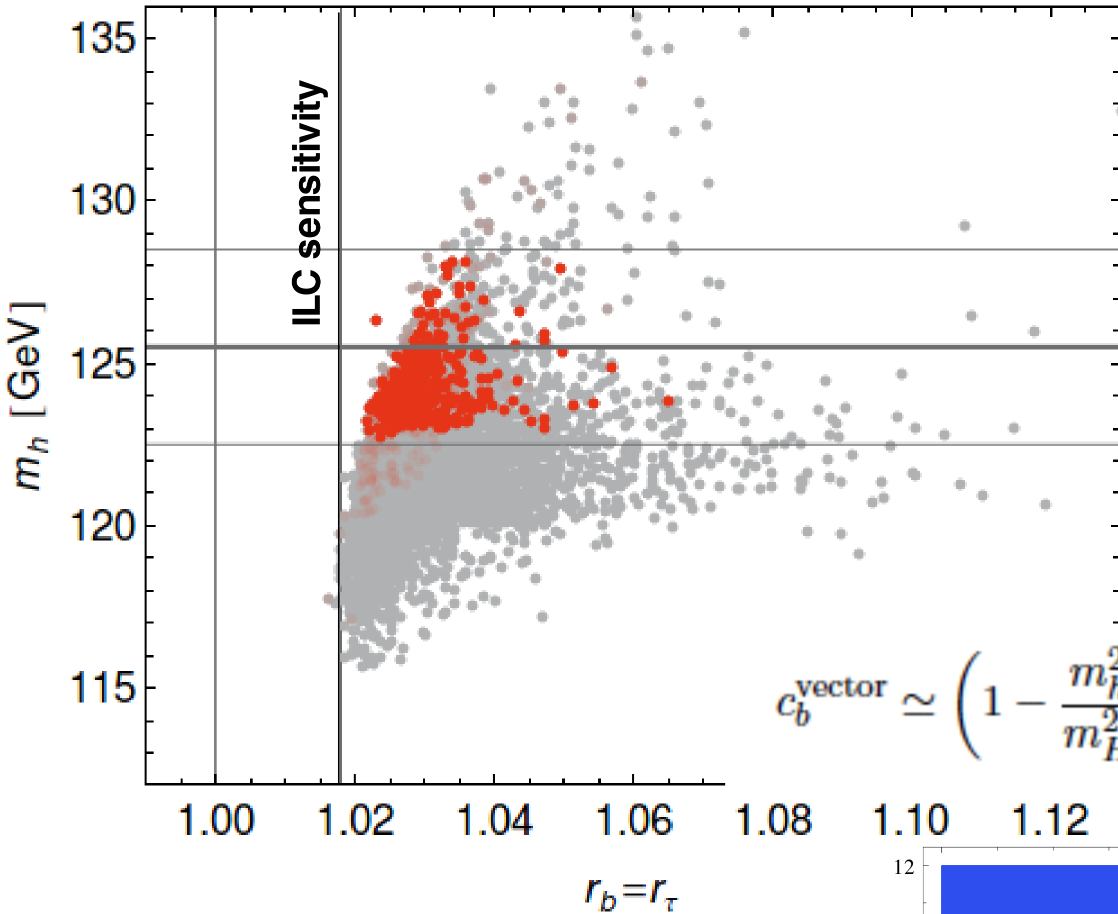


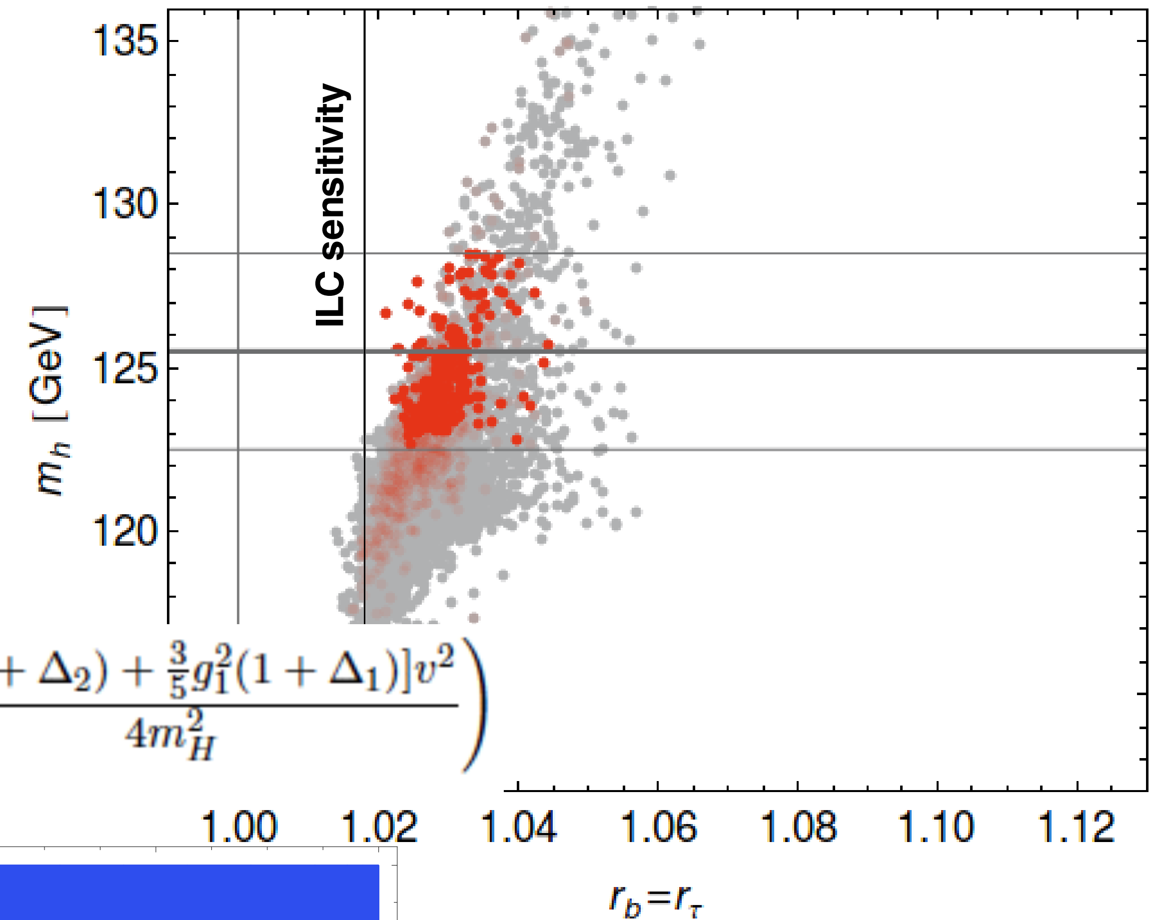




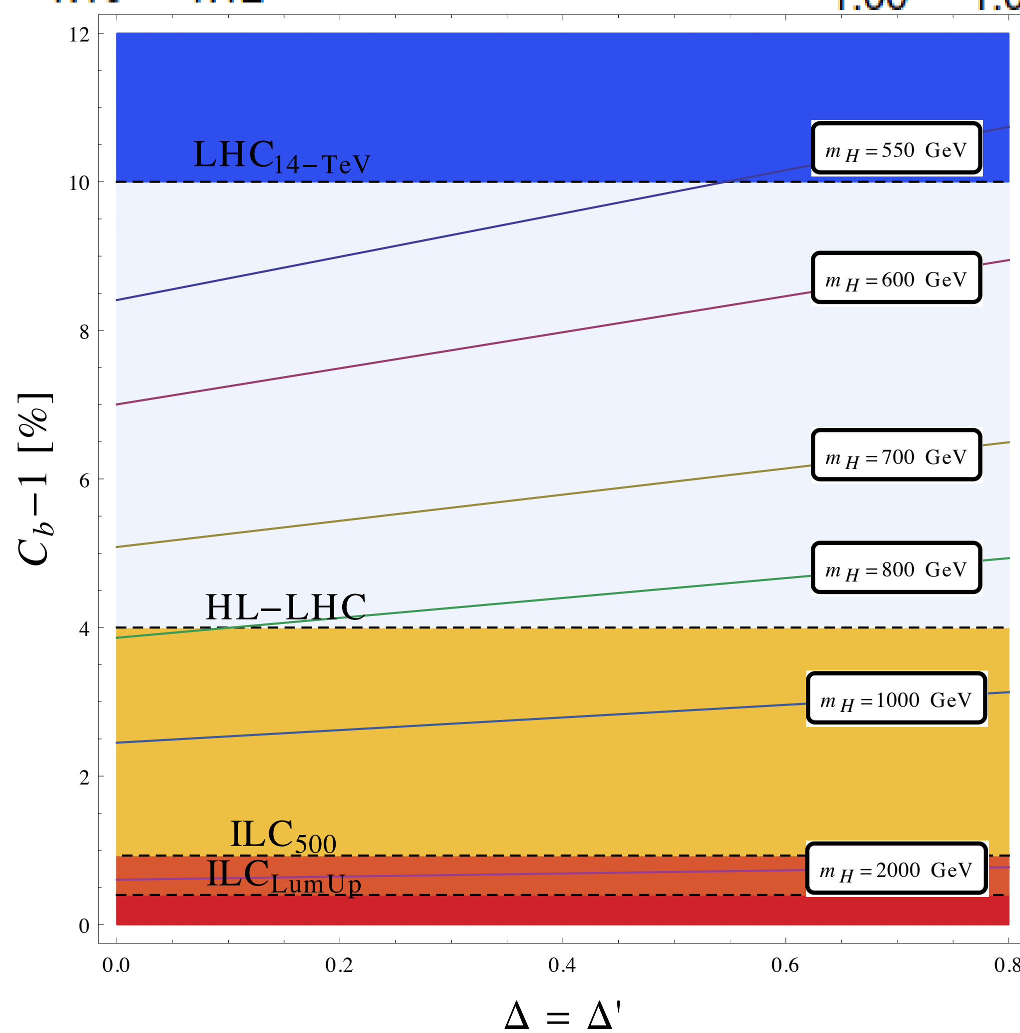


Testable at ILC!



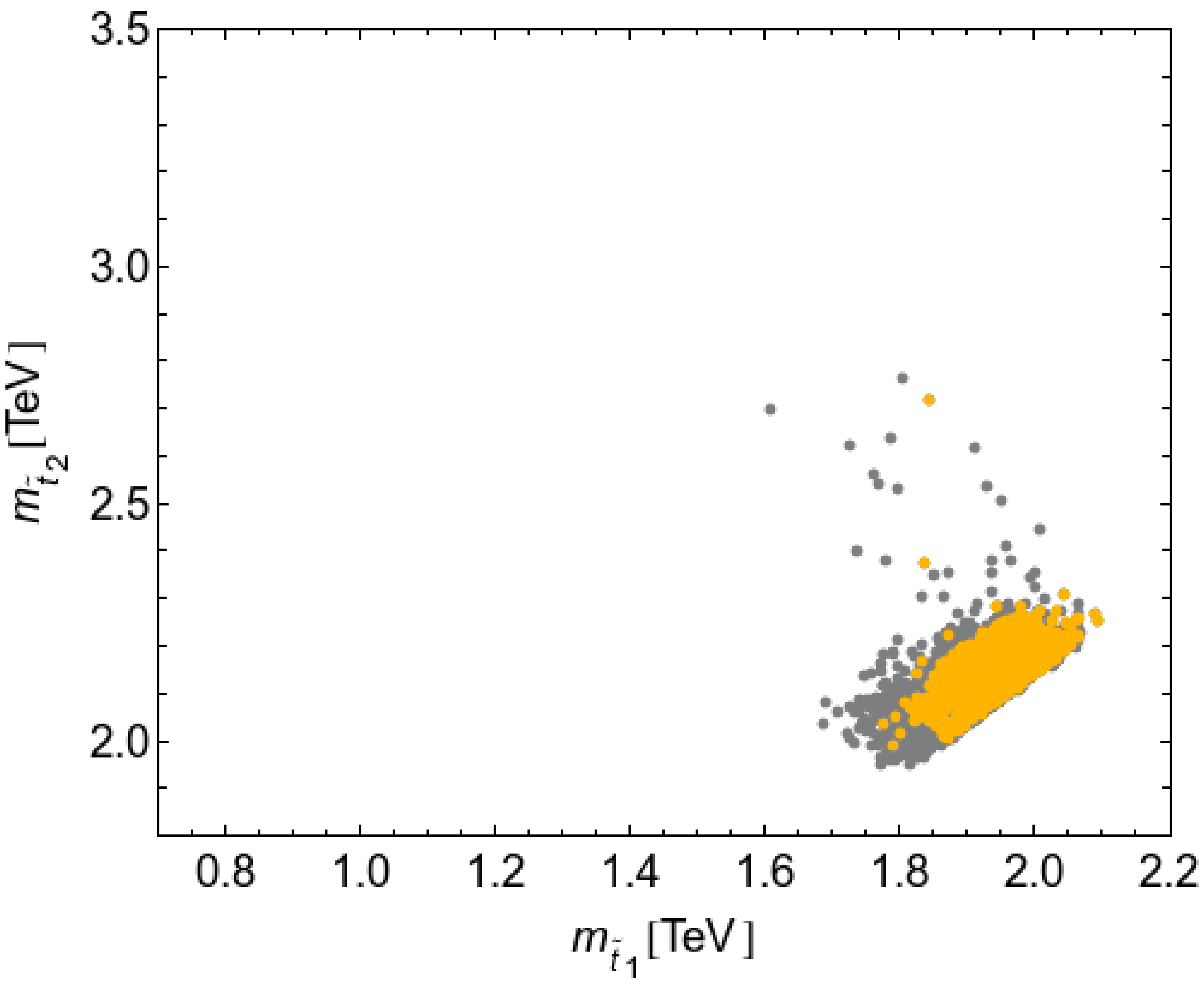


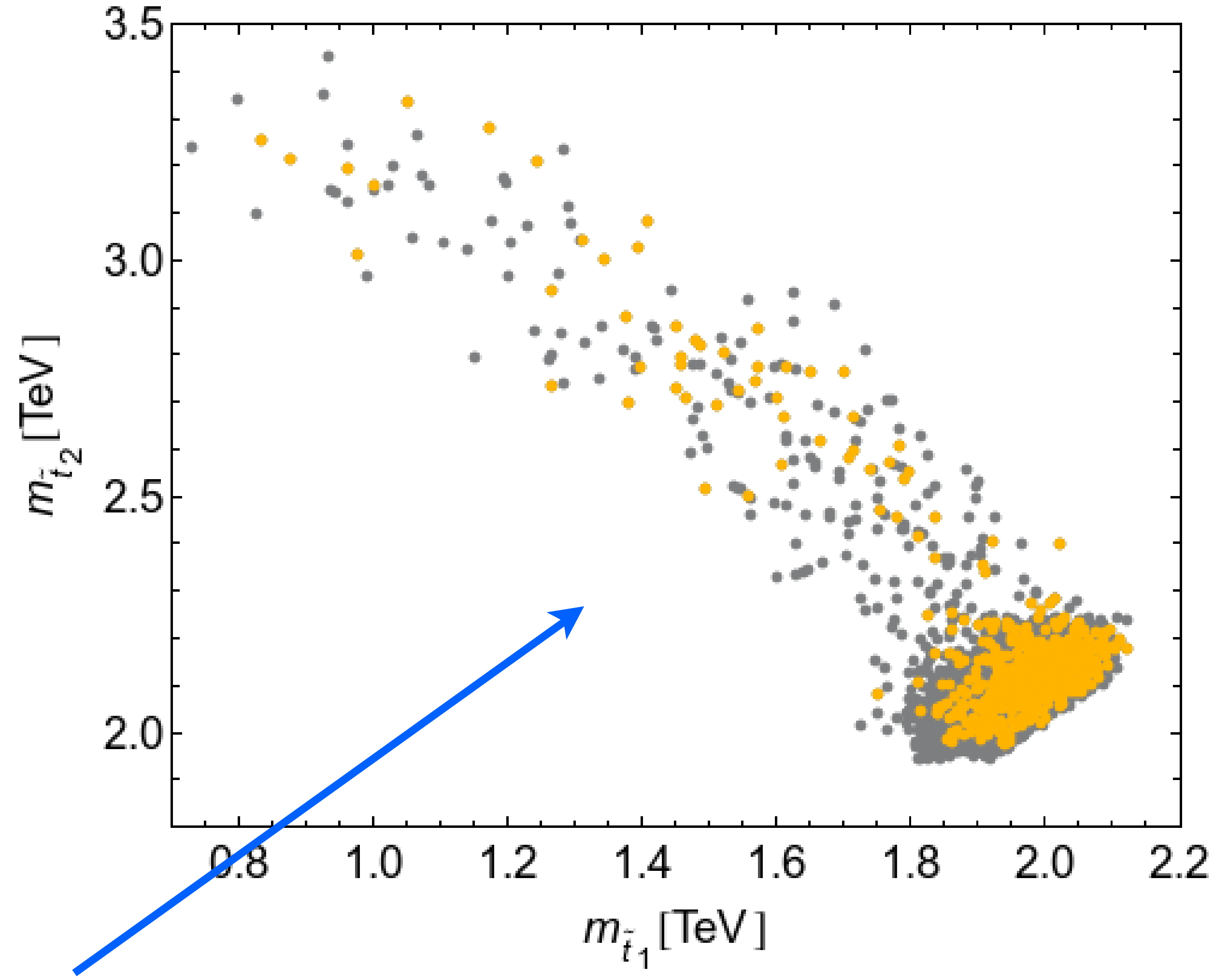
$$c_b^{\rm vector} \simeq \left(1 - \frac{m_h^2}{m_H^2}\right)^{-1} \left(1 + \frac{[g_2^2(1+\Delta_2) + \frac{3}{5}g_1^2(1+\Delta_1)]v^2}{4m_H^2}\right)$$



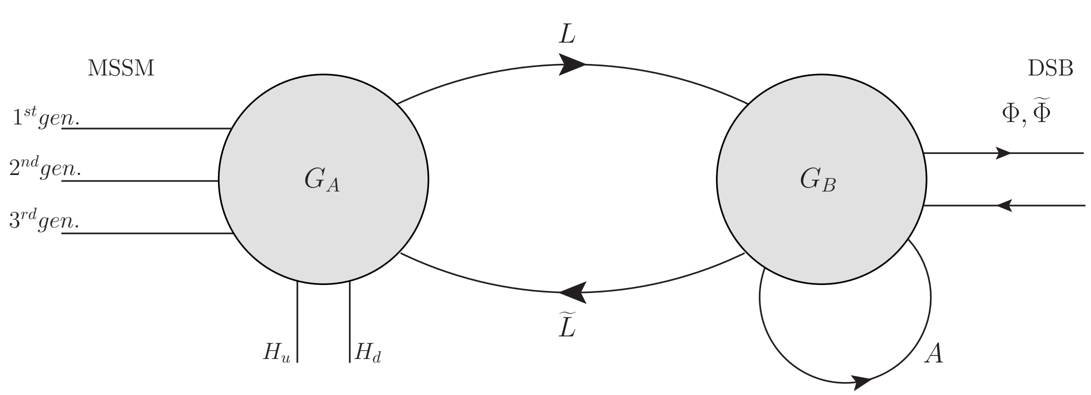
Bharucha, Goudelis, M.M. 1310.4500

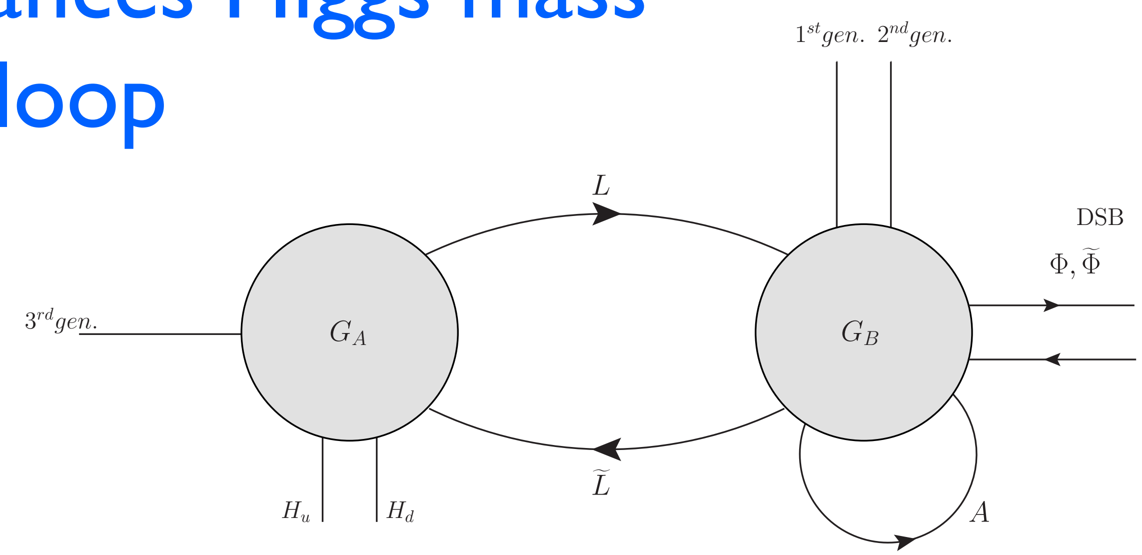
$$m_h^2 \simeq m_z^2 \cos^2(2\beta) + \frac{3}{(4\pi)^2}\frac{m_t^4}{v_{ew}^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right] + \Delta m_{h,1}^2 = \frac{3 m_Z^2}{16\pi^2 v_{ew}^2}\left(1 - \frac{8}{3}\sin\theta_W^2\right)\cos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





Stop splitting enhances Higgs mass
@ 1-loop





Bharucha, Goudelis, M.M. 1310.4500

	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

Conclusions

- Bottom up approach: D-terms are testable at the ILC
- Top down approach: Spectrum generators are available for use

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

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

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

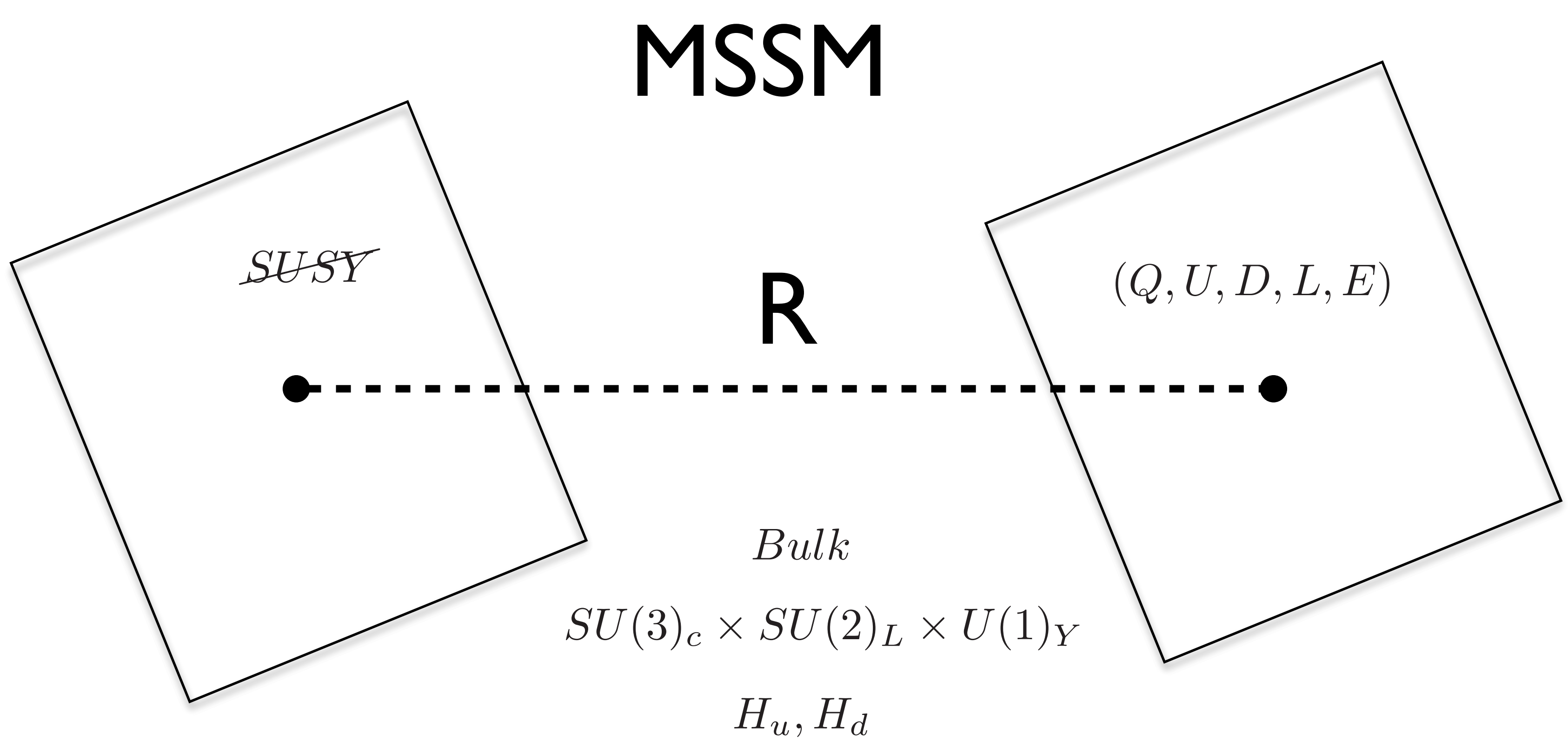
$$X_t = A_t - \mu \cot\beta$$

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 +….
- Need 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

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

(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

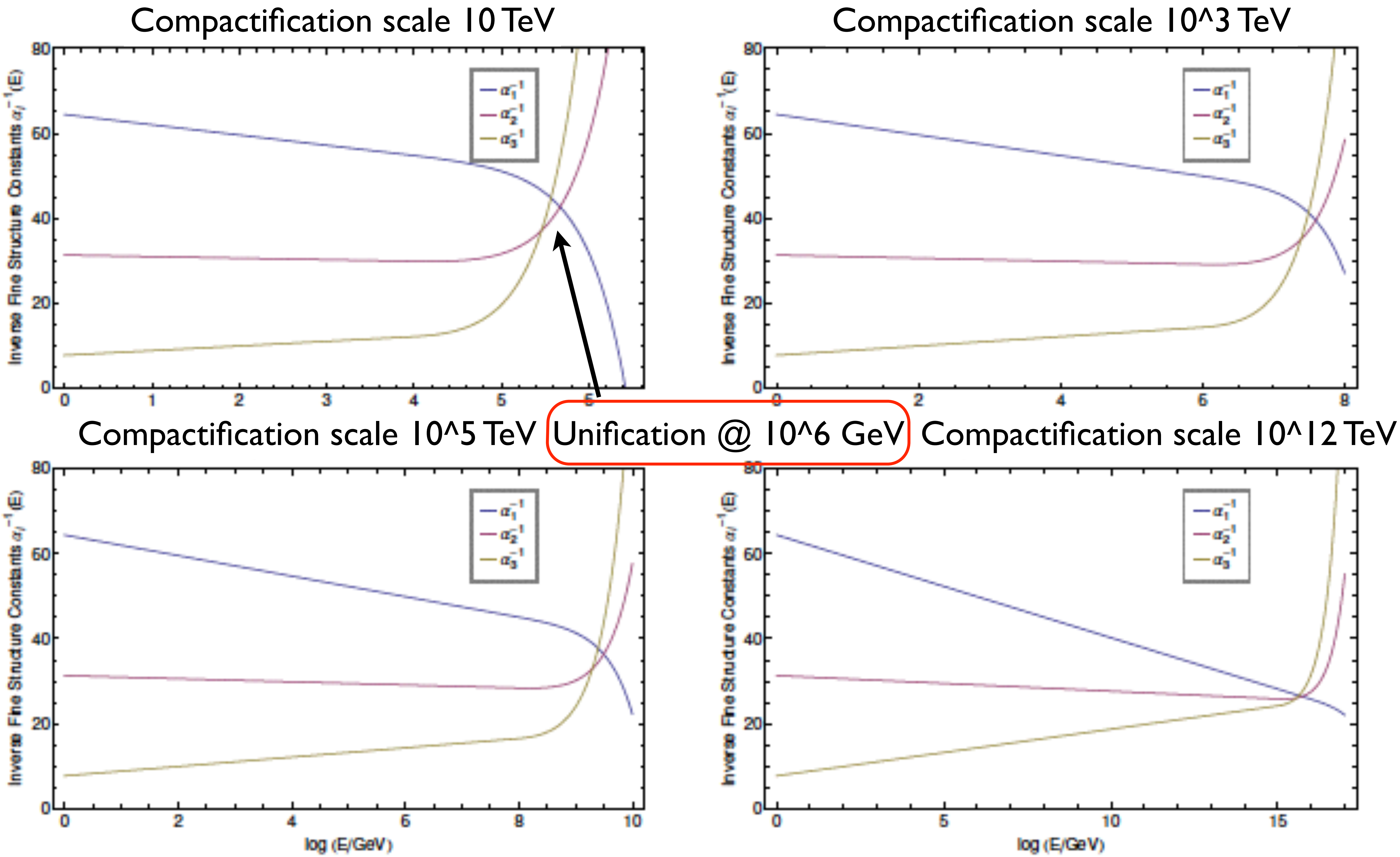


Figure 1. *Running of the inverse fine structure constants $\alpha^{-1}(E)$, for three different values of the compactification scales 10 TeV (top left panel), 10^3 TeV (top right), 10^5 TeV (bottom left) and 10^{12} TeV (bottom right), with M_3 of 1.7 TeV, as a function of log(E/GeV).*

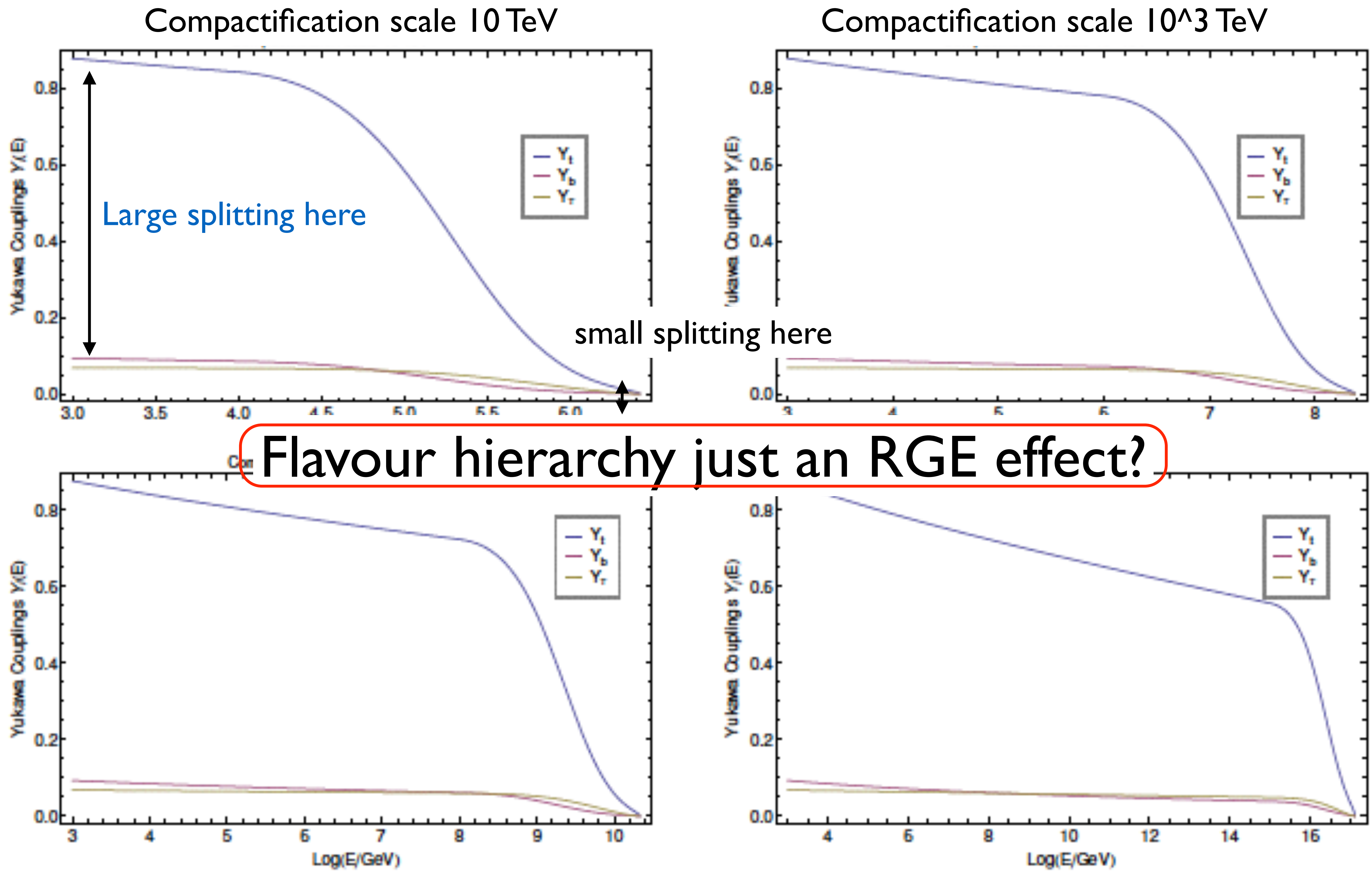


Figure 2. *Running of Yukawa couplings Y_i, for three different values of the compactification scales: 10 TeV (top left panel), 10^3 TeV (top right), 10^5 TeV (bottom left) and 10^{12} TeV (bottom right), with $M_3[10^3]$ of 1.7 TeV, as a function of log(E/GeV).*

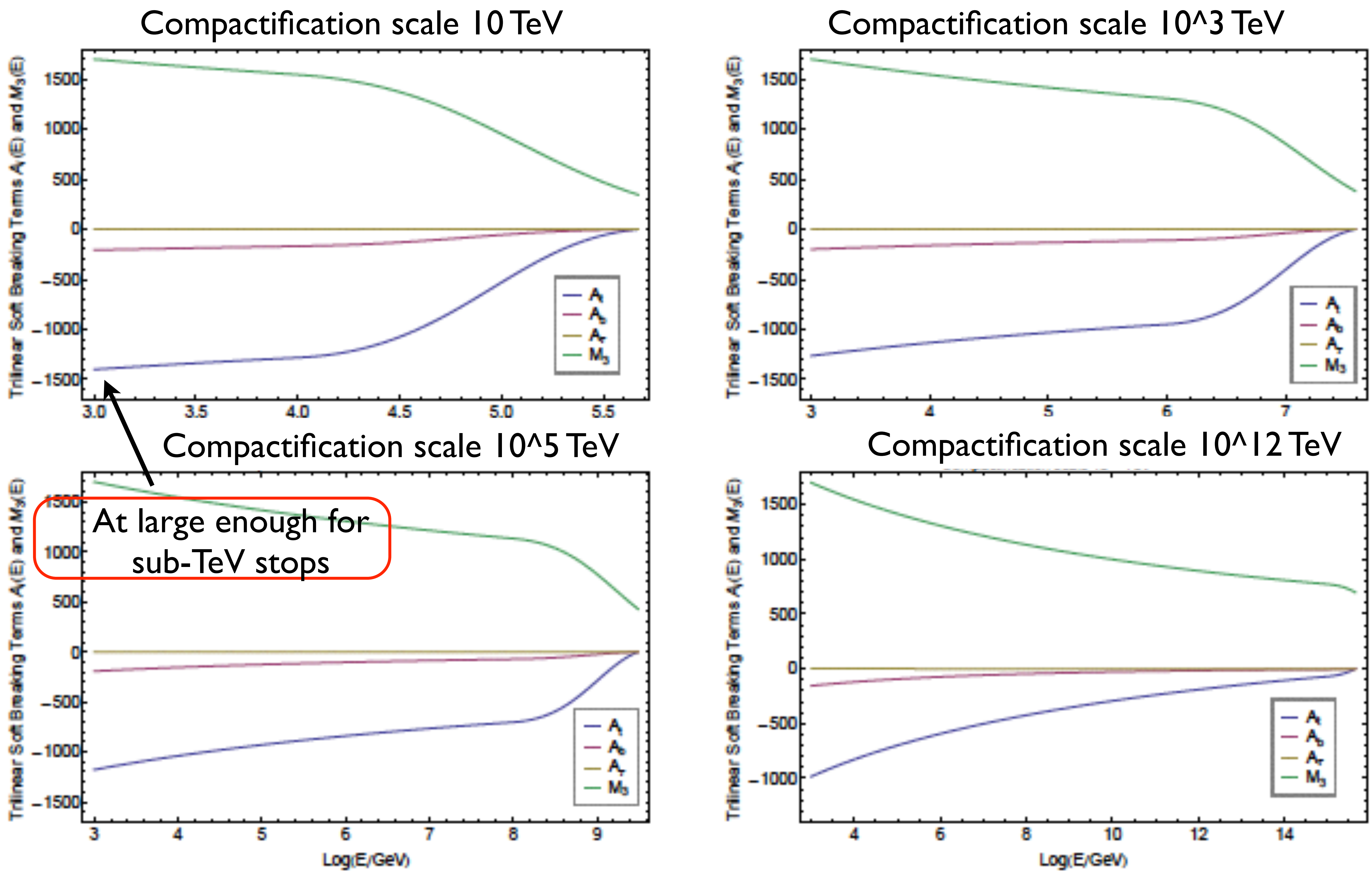
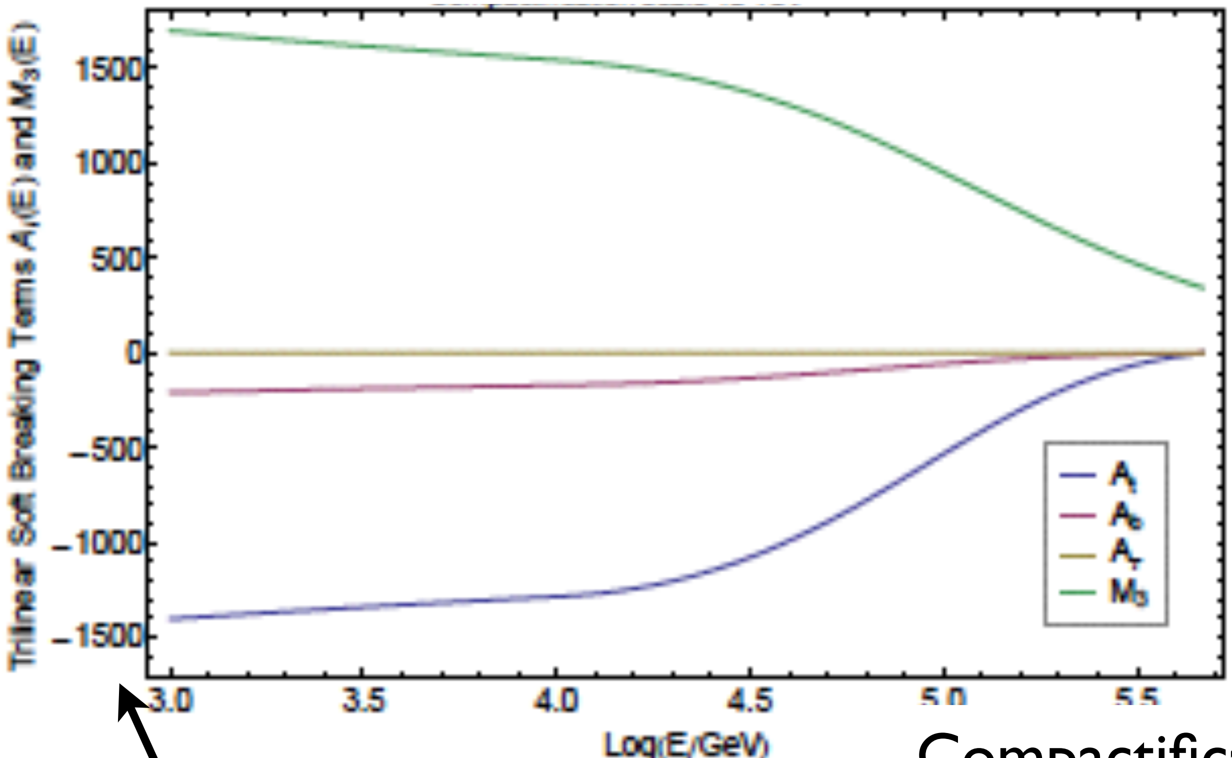
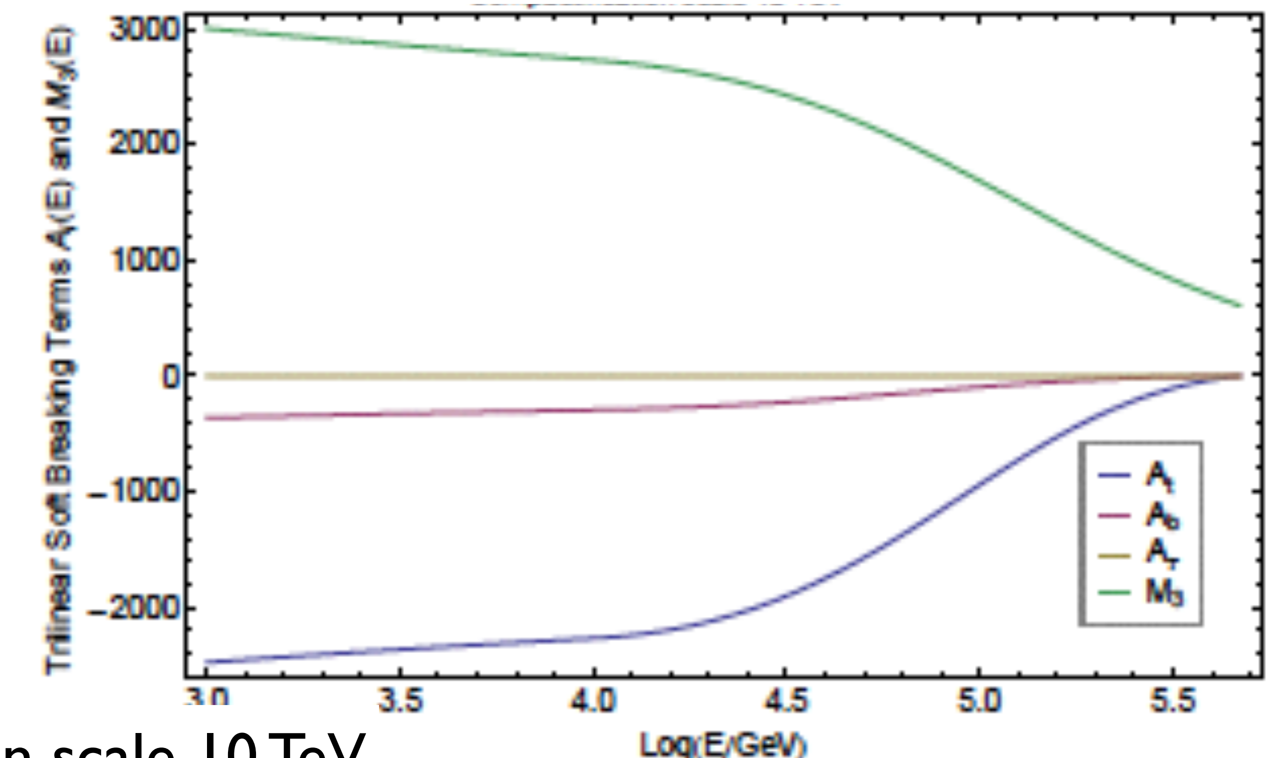


Figure 3. *Running of trilinear soft terms $A_i(3,3)(E)$, for three different values of the compactification scales 10 TeV (top left panel), 10^3 TeV (top right), 10^5 TeV (bottom left) and 10^{12} TeV (bottom right), with $M_3[10^3]$ of 1.7 TeV, as a function of log(E/GeV).*

Compactification scale 10 TeV

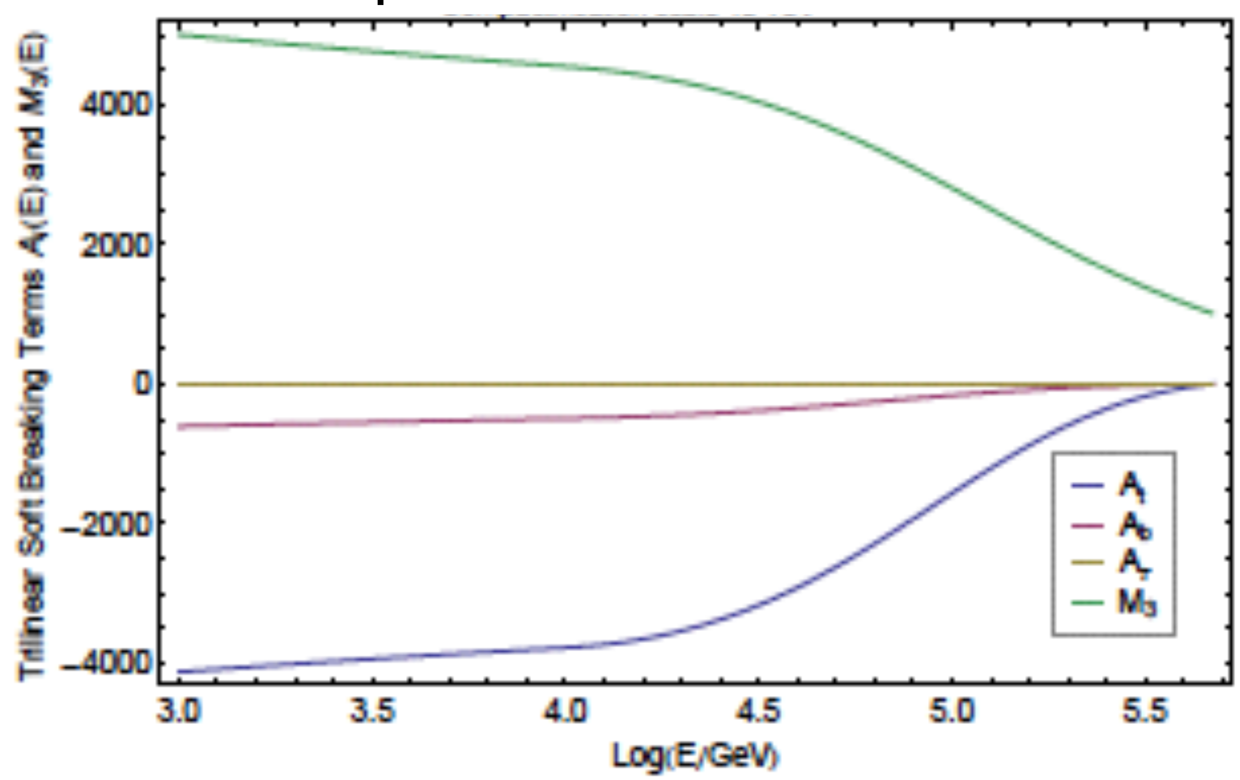


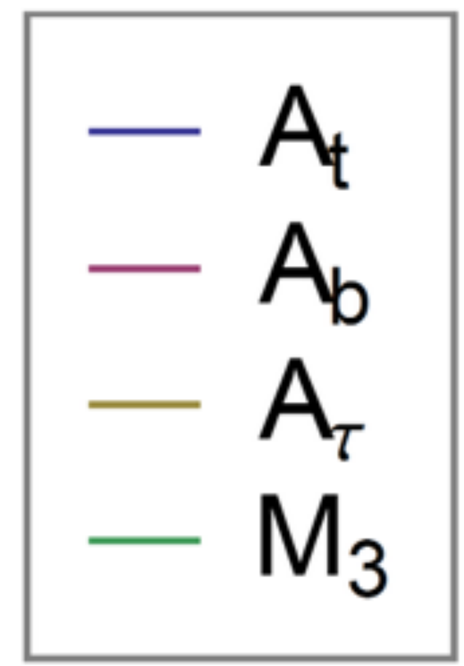
Compactification scale 10 TeV



At large enough for sub-TeV stops

Compactification scale 10 TeV





Larger gluino gives larger At

Thanks for listening!

Conclusions

- Large At with a low unification & SUSY breaking scale
- Is more natural than 4D models
- Can achieve the correct Higgs mass
- Can get light stops and heavy 1st/2nd gen.
- Helps to explain flavour
- Preserves unification and other nice features