A Complete Model of Low-Scale GMSB

Part I

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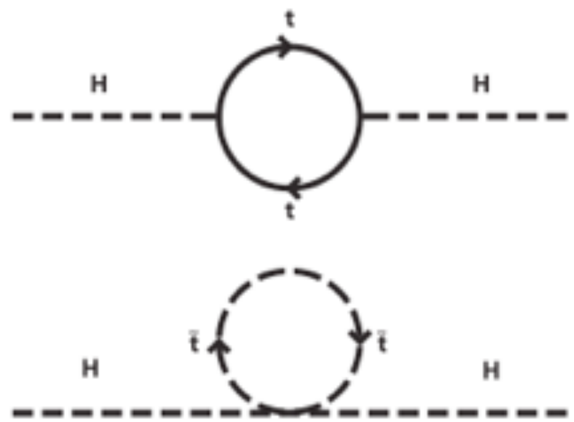
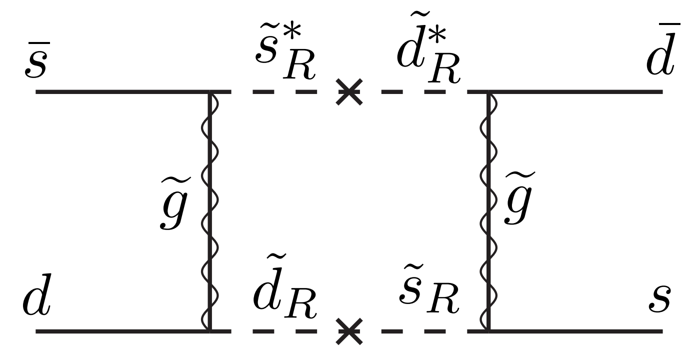
Based on:
Draper, Meade, Reece & DS (1112.3068)
Craig, Knapen, DS & Zhao (1206.4086)

Setting the stage...

Motivation

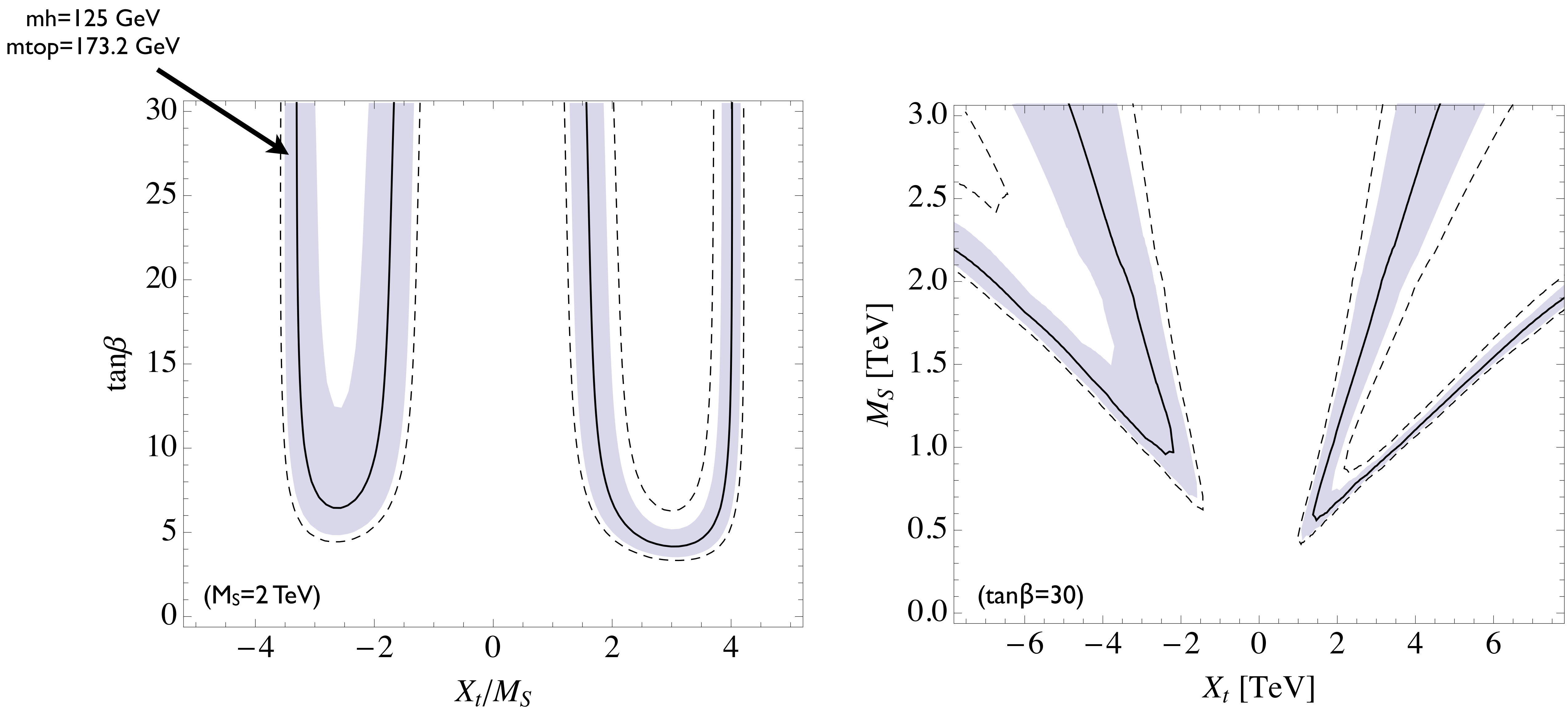




- A SM-like Higgs at 125 GeV renews the urgency of the hierarchy problem. What new physics protects the Higgs mass??
- Supersymmetry is still the best idea for solving the hierarchy problem.
- Gauge mediation (GMSB) is still the best idea for solving the SUSY flavor problem.

Higgs@125 GeV + SUSY + GMSB $\Rightarrow$???

Higgs@125 GeV in the MSSM

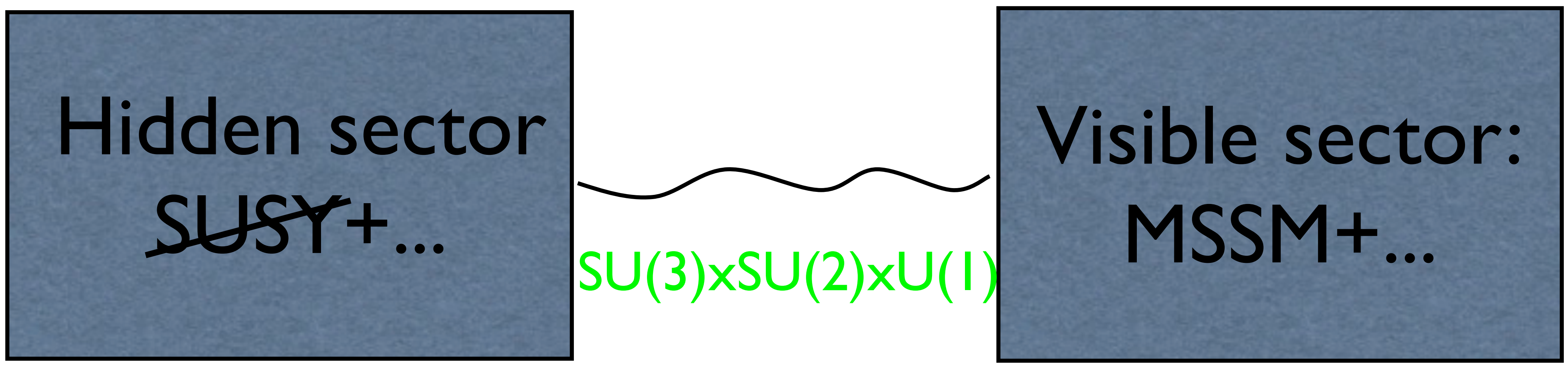


$\tan\beta \gtrsim 3.5$ $\quad M_S \gtrsim 1$ TeV $\quad |X_t| \gtrsim 2$ TeV

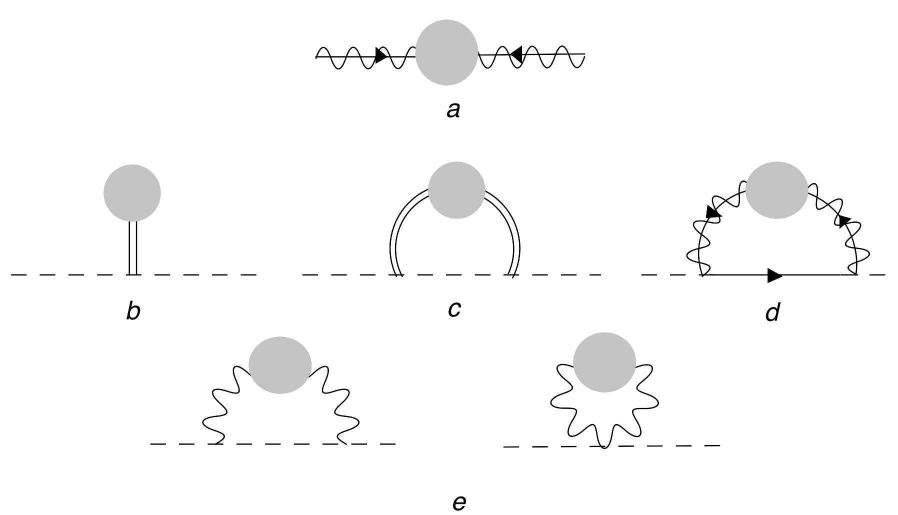
Plots made with FeynHiggs
(Heinemeyer et al)

A-terms must be large in the MSSM!

A-terms in GMSB



- Where do A-terms come from in gauge mediation?
- In GGM, they are not generated at LO in the gauge couplings. So they are always small at the messenger scale.



$$M_r \sim g_r^2 b_r$$

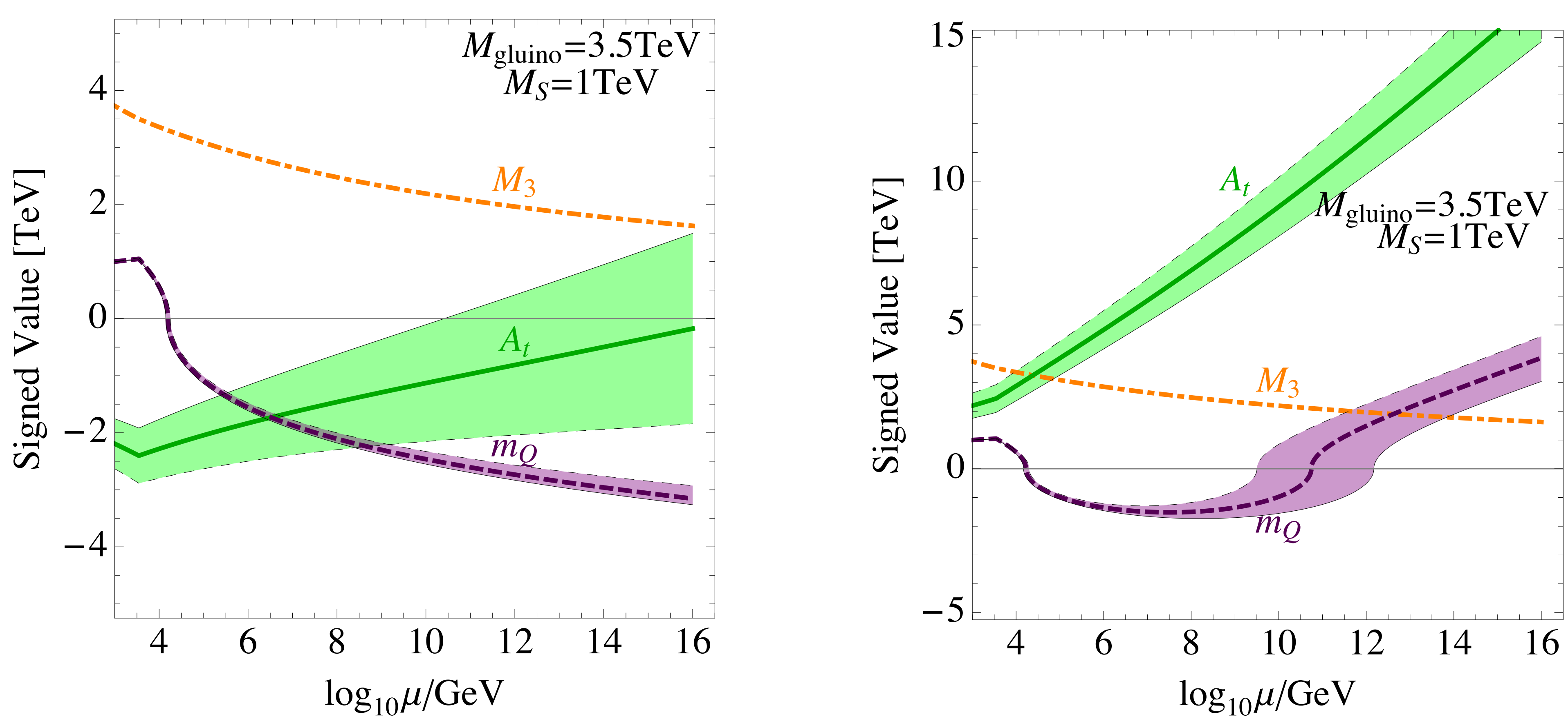
$$m_{\tilde{f}}^2 = \sum_{r=1}^{3} \frac{g_r^4}{(4\pi)^2} c_2(f;r) a_r$$

$$A \sim \frac{g_r^4}{(4\pi)^2}$$

Higgs@125 GeV in the MSSM +GMSB

- Higgs@125 in the MSSM: A-terms must be large at weak scale.
- GGM: A-terms are small at messenger scale.

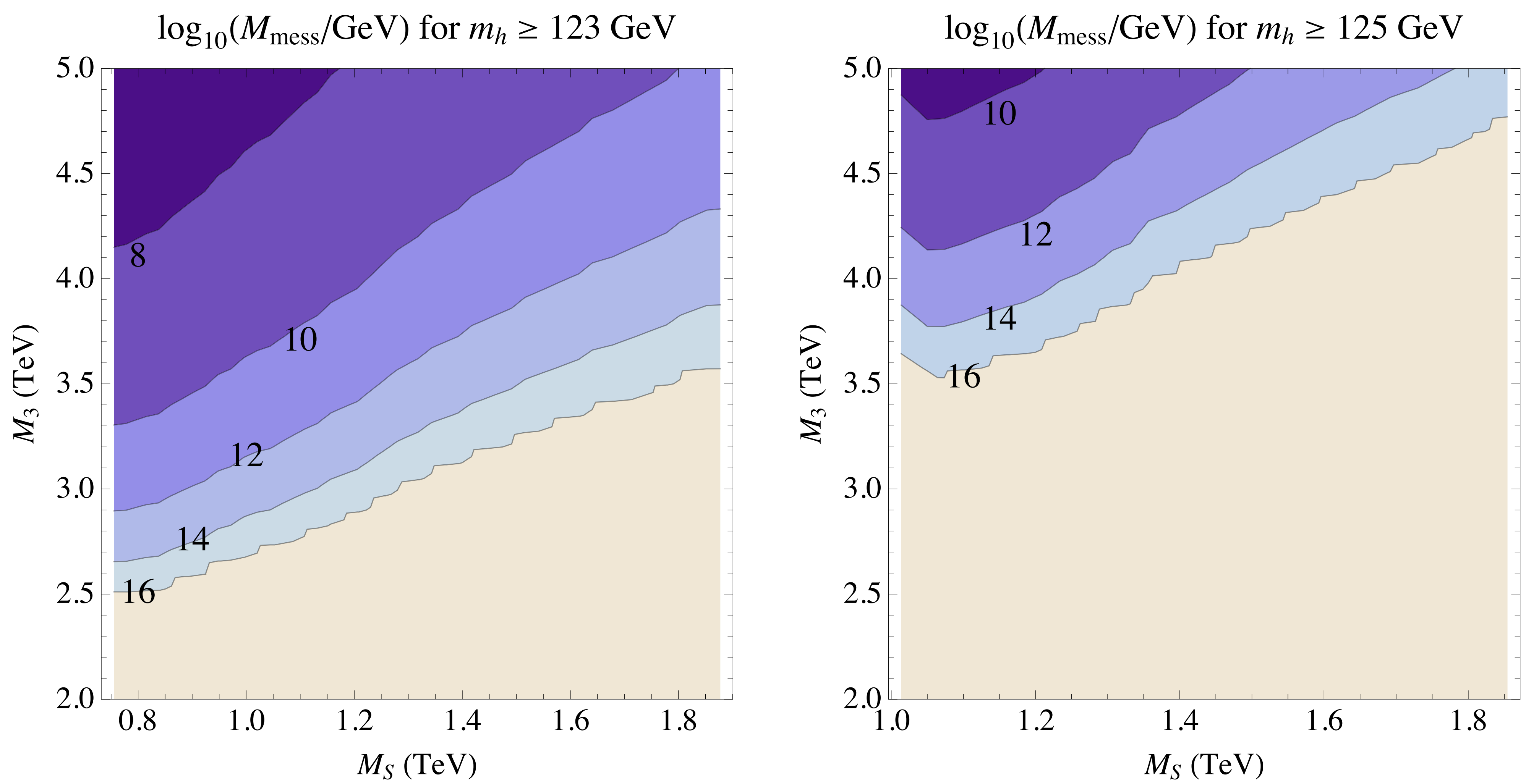
$\Rightarrow$ Run the A-terms up using MSSM RGEs to infer the messenger scale! $\frac{dA_t}{dt} \sim y_t^2 A_t + g_3^2 M_3$



$A_t > 0$ not possible in vanilla GMSB!

Higgs@125 GeV in the MSSM +GMSB

- $A_t < 0$ possible, but requires large M_3 and M_{mess}.



$$M_3 \gtrsim 3 \text{ TeV}, \qquad M_{mess} \gtrsim 10^8 \text{ GeV}$$

Summary so far

- MSSM + GMSB + Higgs@125 => highly constrained
  - Messenger scale must be quite high.
  - Gluinos must be very heavy.
  - Squarks run tachyonic at a relatively low scale. Problems for cosmology? (Maybe not, see e.g. Riotto & Roulet '95; Kusenko et al '96; Carena et al '08)
- Could be the way things are!
- Motivates searches for
  - displaced vertices
  - CHAMPs & R-hadrons
  - EW production
- These are all areas where the LHC could improve markedly.

Can low-scale GMSB be saved?

- The A-term problem is a more severe manifestation of a well-known fact:
- Gauge mediation does a horrible job of modeling the Higgs sector.
- Besides the A-term problem, there is also the long-standing $\mu/B\mu$ problem.
- Maybe these problems are not unrelated...

Question: can we write down a weakly-coupled model that generates large A-terms, μ and $B\mu$ -- all at a low messenger scale?

Can low-scale GMSB be saved?

- As we will see, the answer is a resounding YES.
- In this talk and the next, we will show how to construct and analyze a complete model of low-scale gauge mediation that
    - generates large A-terms
    - mh=125 GeV
    - a viable superpartner spectrum
    - and mu and Bmu.
- Our complete model is simple and economical and highly predictive. We believe it's the first of its kind.

Outline

- Part I (DS)
  - Setting the stage: Higgs@125 in vanilla GMSB
  - How to extend GMSB for large A-terms
    - Analogy between the μ/Bμ and A/mH^2 problems
    - Solution to the A/mH^2 problem
  - A viable model of low-scale GMSB and mh=125
- Part II (NC)
  - Confronting the μ/Bμ problem via the NMSSM
    - Challenges for NMSSM+GMSB
    - Simultaneous solution to the μ/Bμ and A/mH^2 problems
  - A complete model of low-scale GMSB, μ/Bμ, and mh=125
  - Phenomenology & LHC expectations

Extending GMSB

- To generate mu, Bmu and A-terms at the messenger scale, the MSSM and the messengers must be directly coupled somehow.
- The trick is to do this without reintroducing FCNCs and spoiling the main success of GMSB!
- We will focus on weakly coupled messenger+spurion models.
  - For the messengers, let's consider the most general renormalizable superpotential (Cheung, Fitzpatrick & DS)

$$W = (\lambda_{ij} X + m_{ij}) \Phi_i \tilde{\Phi}_j, \qquad \langle X \rangle = M + \theta^2 F$$

  - Add to this general Higgs-messenger couplings

$$\delta W = \lambda_{uij} H_u \Phi_i \tilde{\Phi}_j + \lambda_{dij} H_d \Phi_i \tilde{\Phi}_j$$

(Other options exist, but this is the best for preserving flavor.)

  - Integrating out the messengers will generate μ, $B\mu$, m_{Hu}^2, m_{Hd}^2, A_u, A_d at the messenger scale.

The A/m_H^2 problem

$$\mu \sim \int d^4\theta \, \frac{c_\mu}{M} X^\dagger H_u H_d, \qquad B_\mu \sim \int d^4\theta \, \frac{c_{B\mu}}{M^2} X^\dagger X H_u H_d$$

$$A_u \sim \int d^4\theta \, \frac{c_{A_u}}{M} X^\dagger H_u^\dagger H_u, \qquad m_{H_u}^2 \sim \int d^4\theta \, \frac{c_{m_{H_u}^2}}{M^2} X^\dagger X H_u^\dagger H_u$$

$$\left(\sim c_{A_u} \frac{F}{M} F_{H_u}^\dagger H_u = c_{A_u} \frac{F}{M} Q \lambda_u u H_u\right)$$

messengers

M

- Viable models require: μ, A_u ~ 1-loop; Bμ, $m_{H_u}^2$ ~ 2-loops.
- This is not what one finds in general. Instead,

$\sqrt{F}$

SUSY-breaking spurion X

$$c_\mu \sim c_{B\mu} \sim \frac{\lambda_u \lambda_d}{(4\pi)^2}$$

$$c_{A_u} \sim c_{m_{H_u}^2} \sim \frac{\lambda_u^2}{(4\pi)^2}$$

So just as there's a μ/Bμ problem, there's an A/m_H^2 problem!

In fact, the A/m_H^2 problem is worse, because m_H^2 is a singlet under all global symmetries.

M_{weak}

MSSM

Note, these are problems of any perturbative messenger model for A, mu and Bmu. Not specific to GMSB.

Effective SUSY theory of X+MSSM

The A/m_H^2 problem

$$K_{eff} = Z_u(X, X^\dagger, m_{ij}, \Lambda) H_u^\dagger H_u + Z_d(X, X^\dagger, m_{ij}, \Lambda) H_d^\dagger H_d$$
$$+ \left(Z_\mu(X, X^\dagger, m_{ij}, \Lambda) H_u H_d + c.c. \right)$$

The wavefunctions are in general divergent.

- Let's restate the A/m_H^2 problem more precisely, using the effective Kahler potential.

- At LO in SUSY breaking, the soft terms come from the derivatives of its wavefunction factors:

$$\mu = F \partial_X Z_\mu, \qquad B\mu = |F|^2 \partial_X \partial_{X^\dagger} Z_\mu$$
$$A_u = F \partial_X Z_u, \qquad m_{H_u}^2 = |F|^2 \partial_X \partial_{X^\dagger} Z_u$$

- If the Z's are completely general functions, nothing will prevent Bμ, $m_{H_u}^2$ from appearing at the same loop order as μ, A_u

MGM to the rescue

- There is one loophole to this: minimal gauge mediation!
  (Dine, Nelson et al ’93-’95)

$$m_{ij} = 0 \quad \Rightarrow \quad W = \lambda X \Phi_i \tilde{\Phi}_i + \lambda_{uij} H_u \Phi_i \tilde{\Phi}_j + \lambda_{dij} H_d \Phi_i \tilde{\Phi}_j$$

- If the only source of messenger mass is from X, one-loop $m_{H_u}^2$ will not be generated at leading order in SUSY breaking.

- This phenomenon was noticed already in the early literature (Dine, Nir, Shirman ’96; Dvali, Giudice & Pomarol ’96). But it was seen as a curiosity, an accidental cancellation.

- In fact, it is a direct consequence of the symmetries of MGM.

MGM to the rescue

$$W = \lambda X \Phi_i \tilde{\Phi}_i + \lambda_{uij} H_u \Phi_i \tilde{\Phi}_j + \lambda_{dij} H_d \Phi_i \tilde{\Phi}_j$$

- Here is the general argument:
  - Model has a $U(1)_R$ under which

    $$R(X) = R(H_u) = R(H_d) = 2, \;\; R(\Phi) = R(\tilde{\Phi}) = 0$$

  - So must have

    $$Z_{u,d} = Z_{u,d}(XX^\dagger/\Lambda^2), \quad Z_\mu = \frac{X^\dagger}{X} \tilde{Z}_\mu(XX^\dagger/\Lambda^2)$$

  - Furthermore, at one-loop we can have at most a log divergence:

    $$Z^{(1)}_{u,d} = a\lambda^2_{u,d} \log XX^\dagger/\Lambda^2, \quad Z^{(1)}_\mu = \lambda_u \lambda_d \frac{X^\dagger}{X}(b + c \log XX^\dagger/\Lambda^2)$$

  - So $m^2_{H_u} \sim \partial_X \partial_{X^\dagger} Z^{(1)}_{u,d}$ vanishes!

MGM to the rescue

$$Z^{(1)}_{u,d} = a\lambda^2_{u,d}\log XX^\dagger/\Lambda^2, \quad Z^{(1)}_\mu = \lambda_u\lambda_d \frac{X^\dagger}{X}(b + c\log XX^\dagger/\Lambda^2)$$

- Note that the same does not apply to $B\mu \sim \partial_X \partial_{X^\dagger} Z^{(1)}_\mu$.
- Here one must work much harder in the same context (see e.g. Giudice, Kim & Rattazzi '07)
- But if we turn off λ_d, then we can have a viable model of large A-terms!
- As we will see, this can be accomplished with a $U(1)_X$ symmetry which treats Hu and Hd differently.

The A/m_H^2 problem redux

- So MGM solves the A/m_H^2 problem, rejoice! Low-scale GMSB is saved!
- Wait a minute. Not so easy....
- Even after solving the main A/m_H^2 problem, a residual problem remains.
    - For m_h = 125 GeV, we have seen that we need $A_t \sim m_{stop}$.
    - Even if we find a way to kill m_{Hu}^2 at one-loop, we will never be able to kill it at two loops.
    - So parametrically we expect $m_{Hu}^2 \sim A_t^2 \sim m_{stop}^2$.
    - If m_{Hu}^2 is positive, this will ruin low-scale radiative EWSB!

Model I:
Low-scale GMSB with large A-terms

The model

$$W = \lambda X \Phi_i \cdot \tilde{\Phi}_i + \lambda_{uij} H_u \cdot \Phi_i \cdot \tilde{\Phi}_j + y_t H_u \cdot Q \cdot U + \mu H_u \cdot H_d$$

- Most general superpotential consistent with
  - Messenger number
  - U(1)x : $q_X(X, \Phi_i, \tilde{\Phi}_i, H_u, H_d) = (1, -1/2, -1/2, 1, -1)$
- i,j range over SU(3)xSU(2)xU(1) irreps.
- Messenger irreps consistent with SU(5) GUT:
  - 5+5bar : $(\Phi_1, \Phi_2, \Phi_3) = ((\mathbf{1}, \mathbf{1}, 0), (\mathbf{1}, \mathbf{2}, 1/2), (\mathbf{3}, \mathbf{1}, -1/3))$
  - 10+10bar: $(\Phi_1, \Phi_2, \Phi_3) = ((\mathbf{3}, \mathbf{1}, 2/3), (\mathbf{3}, \mathbf{2}, 1/6), (\mathbf{1}, \mathbf{1}, 1))$

The soft terms

Messenger number helps with At/mstop ratio.

- Schematically, we have

Need $\lambda_u \sim g_3 \sim 1$ to get At ~ mstop

A-terms always negative. Is this a theorem?

$$A_u \sim -\frac{N_{eff}\alpha_{\lambda_u}}{4\pi}\Lambda$$

$$\delta m^2_{H_u} \sim \frac{N_{eff}\alpha_{\lambda_u}}{4\pi}\left(-\left(\frac{\Lambda}{M}\right)^2 + \frac{N_{eff}\alpha_{\lambda_u}}{4\pi} - \sum_{r=1}^{3}\frac{c_r\alpha_r}{4\pi}\right)\Lambda^2$$

$$\delta m^2_{\tilde{t}} \sim -\frac{N_{eff}\alpha_t\alpha_{\lambda_u}}{(4\pi)^2}\Lambda^2$$

- Λ = F/M; N_{eff}=effective messenger number

Ultimate limiting factor: stop tachyon prevents us from making A term arbitrarily large

One-loop, F/M^2 suppressed contribution is always negative!
This will be the hero of our story!
It's crucial for EWSB at low messenger scales!!

Gauge couplings contribute negatively at two-loops. If messengers carry color, this can also help with EWSB

The KLLTY analysis

- This idea was explored recently in a paper of Kang, Li, Liu, Tong & Yang, 1203.2336.
- For a model with a 10+10bar messengers, they found:

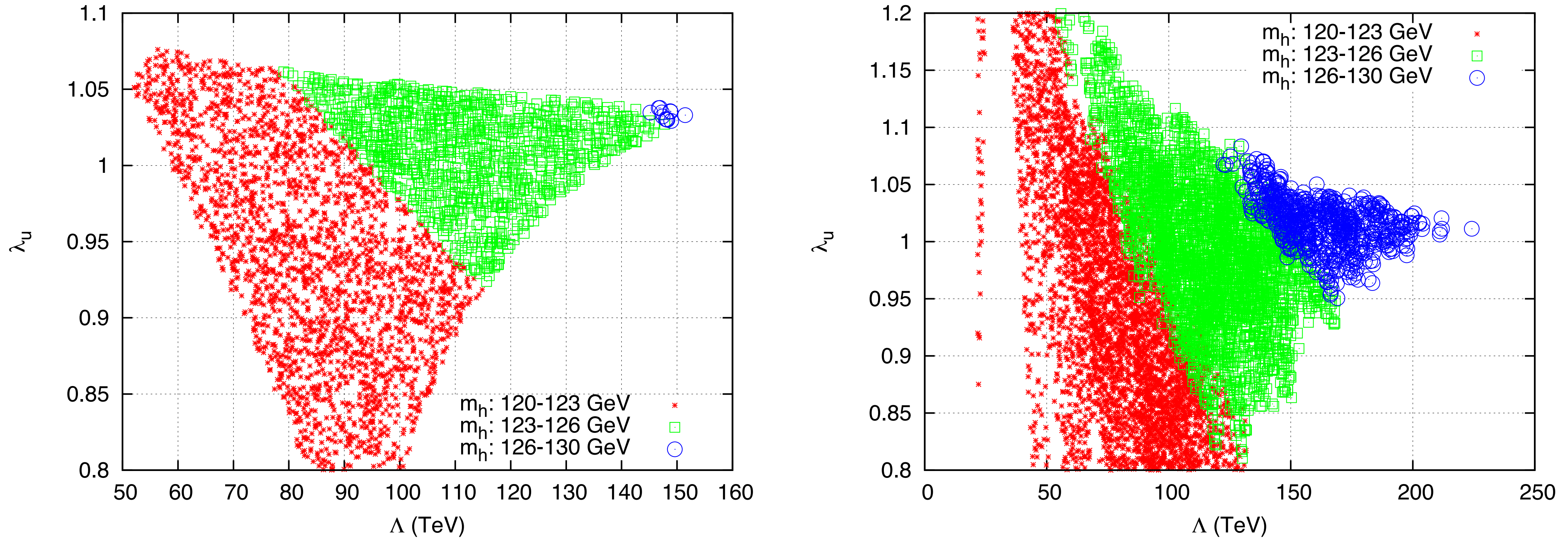
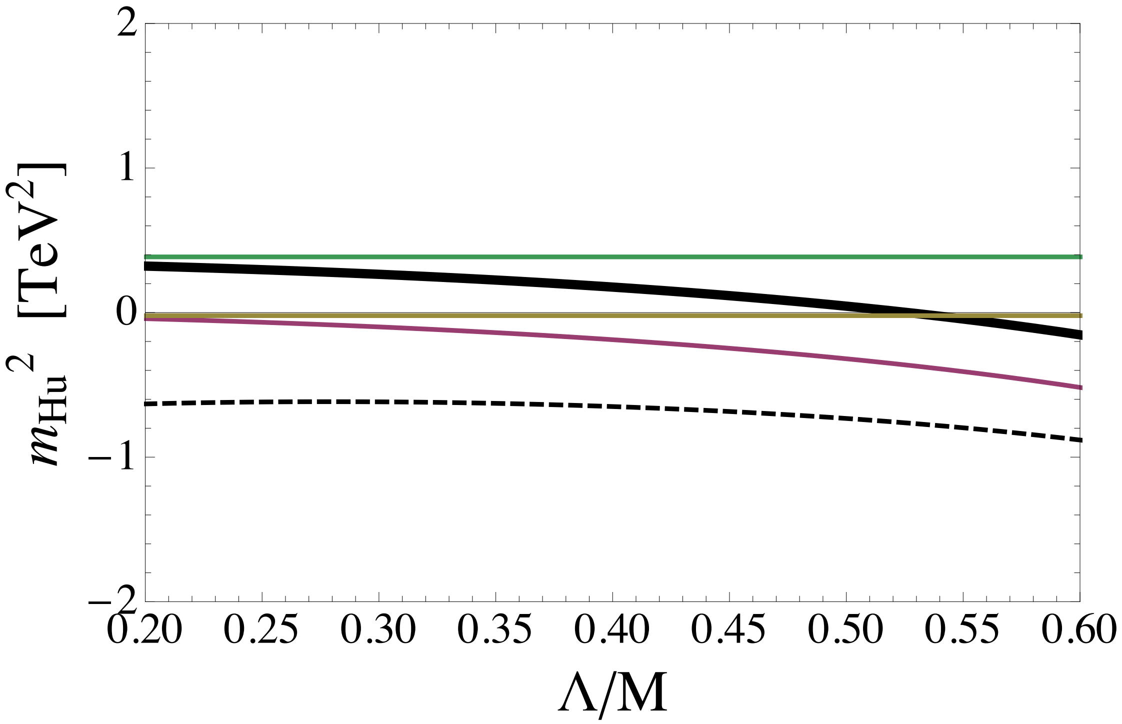


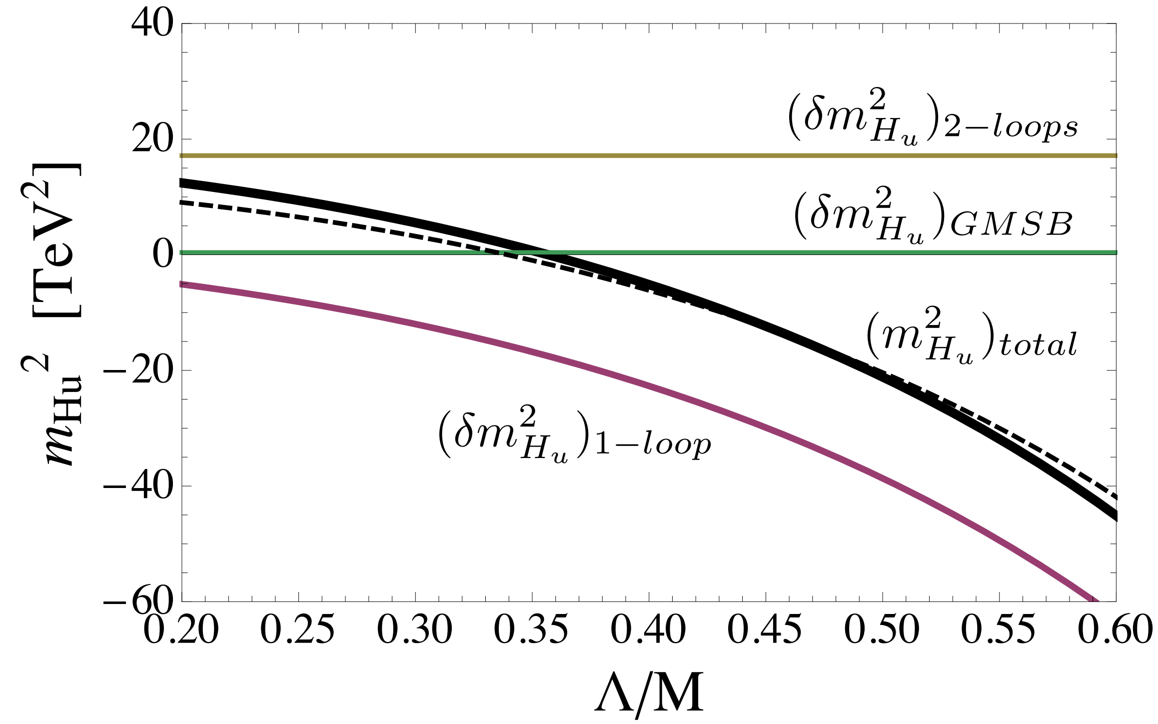
FIG. 4: Scatter plots of viable parameter space projected on the planes of λ_u versus Λ. The messenger mass scale is fixed to be 5×10^8 GeV for the left panel and 5×10^{12} GeV for the right.

Rescuing low-scale GMSB

- Kang et al were forced to take high messenger scales, because they did not include the one-loop, F/M^2 suppressed, negative contribution to m_{Hu}^2. So they needed to run a long time for EWSB.
- By taking this into account, we can rescue low messenger scales!



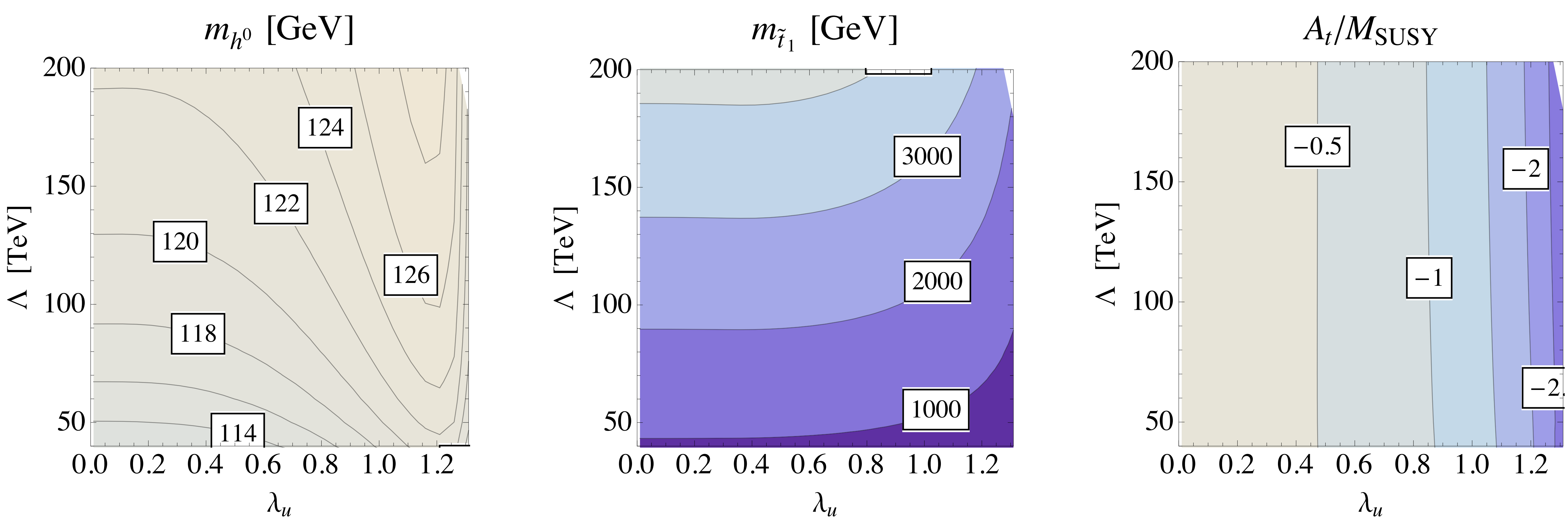
(λ_u = 0.1)



(λ_u = 1.1)

Rescuing low-scale GMSB

mh=125 is easily possible, with Mmess~100 TeV and mstop~1.5 TeV.



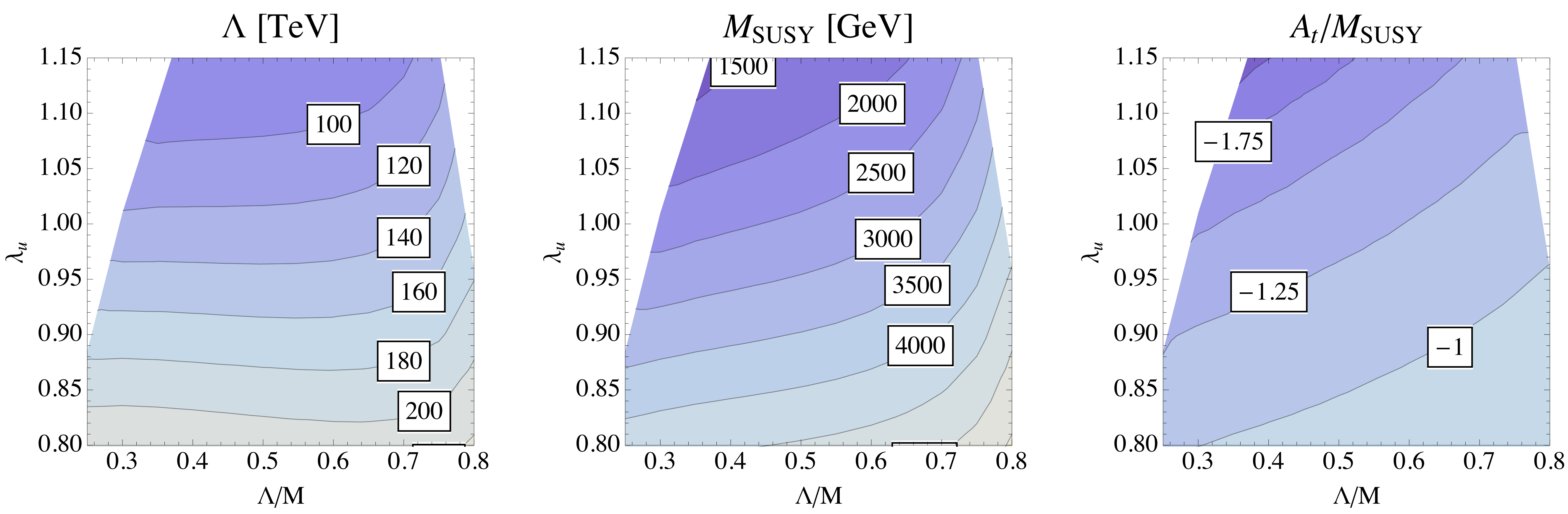
5+5bar messengers, N_{mess}=4, M=2Λ, tanβ=10

Plots made with SoftSUSY

Rescuing low-scale GMSB

For a given choice of Λ/M, can always achieve mh=125 by making Λ (and hence mstop) large enough.

So if we solve mh=125 for Λ, we obtain a complete characterization of the model in the $(\lambda_u, \Lambda/M)$ plane!



For more detailed discussion of the spectrum and pheno, see Nathaniel's talk!

Conclusion to Part I

- So far, what we have done can be viewed as a module to attach to any model of GMSB, e.g. GGM.
- So we could in principle get m_h=125 while preserving all the general signatures of low-scale SUSY-breaking.
- But what if we want to do something more minimal? Still need to get μ and $B\mu$ somehow.
- Challenging with the MSSM, for reasons mentioned above.
- But what about the NMSSM? In fact, this is an extremely natural direction!!
- For the complete model of low-scale gauge mediation, stay tuned for Nathaniel's talk...

The End