A Complete Model of Low-Scale Gauge Mediation

Yue Zhao
SLAC/Stanford

UC Davis Theory Seminars
Oct. 1st, 2012

arXiv:1206.4086
Nathaniel Craig, Simon Knapen, David Shih, Yue Zhao.

Outline:

- Motivation
- General problem and solution
- Model I: MSSM with large A term

  phenomenological problems: EWSB and tachyonic sfermions
- Model II: NMSSM with large A terms, μ and B μ
- Phenomenology
- Landau Poles
- Summary

References

.
.
.

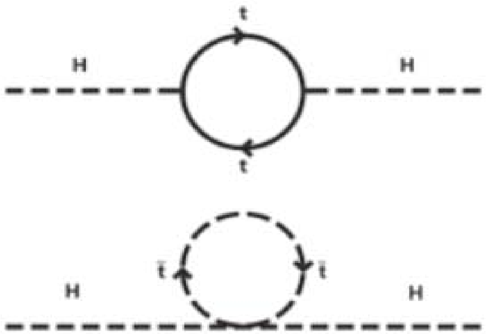
arXiv:9603238 G. Dvali, G. Giudice, and A. Pomarol
arXiv:9607397 M. Dine, Y. Nir, and Y. Shirman
arXiv:9705307 S. Dimopoulos, G. Dvali, R. Rattazzi, and G. Giudice
arXiv:9706540 G. Giudice and R. Rattazzi
arXiv:9711264 A. de Gouvea, A. Friedland, and H. Murayama
arXiv:0112190 Z. Chacko, Eduardo Ponton
arXiv:0706.3873 A. Delgado, G. Giudice, and P. Slavich
arXiv:0709.0775 H. Murayama, Y. Nomura, and D. Poland
arXiv:0711.4448 G. F. Giudice, H. D. Kim, and R. Rattazzi
arXiv:0812.3900 Z. Komargodski and N. Seiberg
arXiv:1103.0292 Yael Shadmi, Peter Z. Szabo
arXiv:1107.3006 Jason L. Evans, Masahiro Ibe, Tsutomu T. Yanagida
arXiv:1111.4519 Lawrence J. Hall, Yasunori Nomura
arXiv:1112.2703 L. J. Hall, D. Pinner, and J. T. Ruderman
arXiv:1112.3026 S. Heinemeyer, O. Stal, and G. Weiglein
arXiv:1112.3028 A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, and J. Quevillon

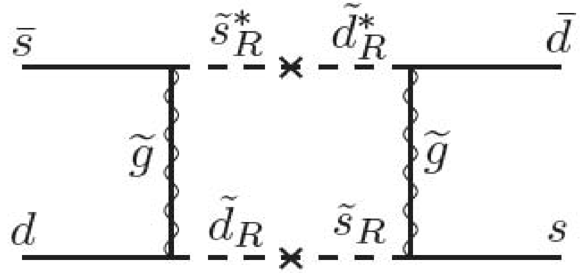
References

arXiv:1112.3032 A. Arbey, M. Battaglia, and F. Mahmoudi
arXiv:1112.3068 P. Draper, P. Meade, M. Reece, and D. Shih
arXiv:1112.3336 M. Carena, S. Gori, N. R. Shah, and C. E. Wagner
arXiv:1201.2611 J. L. Evans, M. Ibe, S. Shirai, T. T. Yanagida
arXiv:1201.6045 John Ellis, Mary K. Gaillard, Dimitri V. Nanopoulos.
arXiv:1202.5821 J. Cao, Z. Heng, J. M. Yang, Y. Zhang, and J. Zhu
arXiv:1202.6339 Grant Larsen, Yasunori Nomura, Hannes L.L. Roberts
arXiv:1203.0572 Nathaniel Craig, Savas Dimopoulos, Tony Gherghetta
arXiv:1203.2336 Z. Kang, T. Li, T. Liu, C. Tong, and J. M. Yang
arXiv:1203.3207 N. D. Christensen, T. Han, and S. Su
arXiv:1204.5977 F. Brummer, S. Kraml, and S. Kulkarni
arXiv:1206.4993 H. Murayama, Y. Nomura, S. Shirai, K. Tobioka
arXiv:1206.5301 Gilly Elor, Lawrence J. Hall, David Pinner, Joshua T. Ruderman
arXiv:1207.0234 Clifford Cheung, Hannes L. Roberts

.
.
.

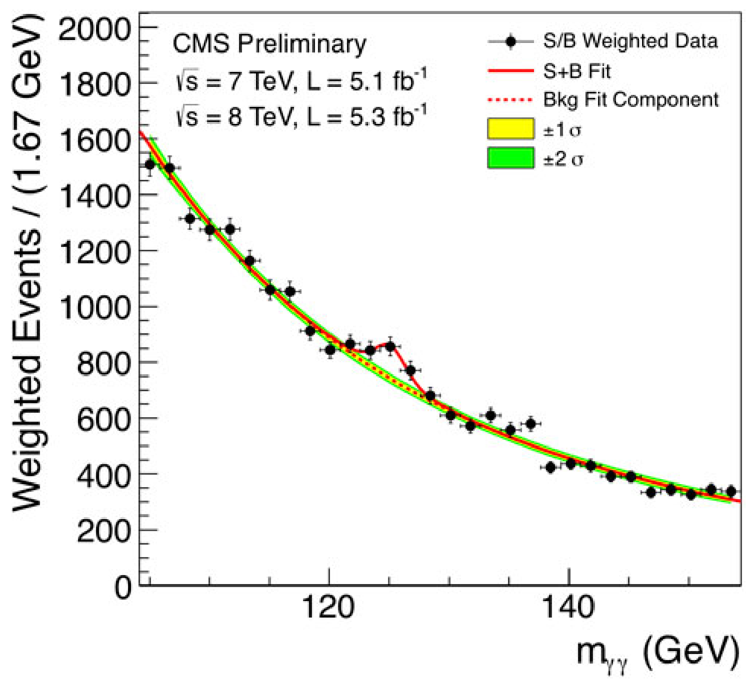
Motivation





SUSY ⇨ hierarchy problem

GMSB ⇨ flavor problem



125 GeV Higgs

How does GMSB generate 125 GeV Higgs consistently ?

Motivation

For MSSM

$$m_h^2 = m_Z^2 \frac{(\tan^2\beta - 1)^2}{(\tan^2\beta + 1)^2} + \frac{3m_t^4}{4\pi^2 v^2}\left[\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right] + \ldots$$

tree level contribution
max at large tanβ

dominant loop contribution

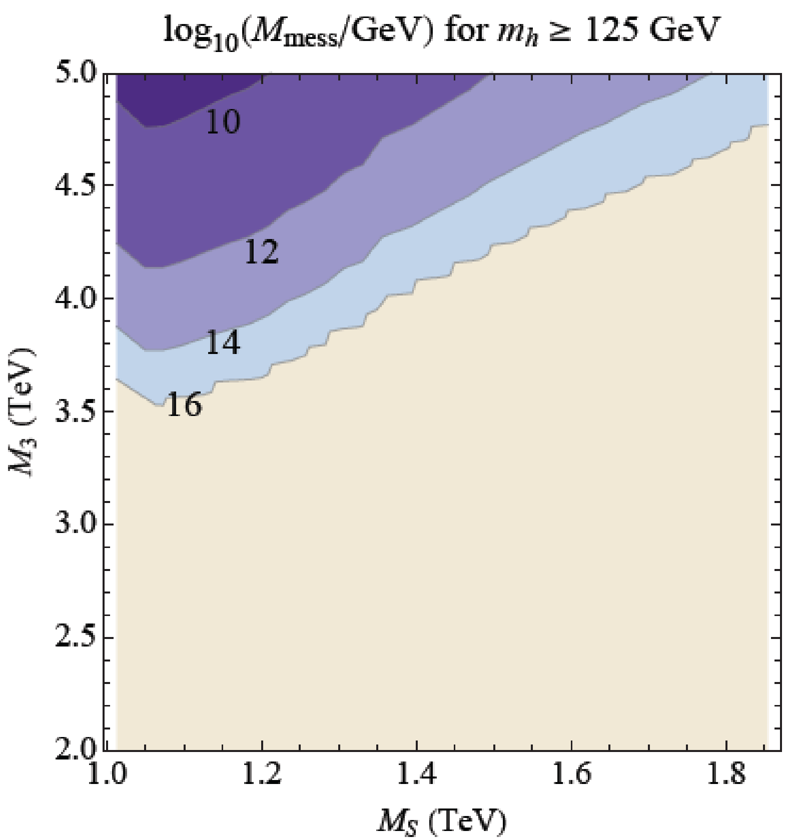
polynomial dependence
on mixing Xt/Ms
max at √6

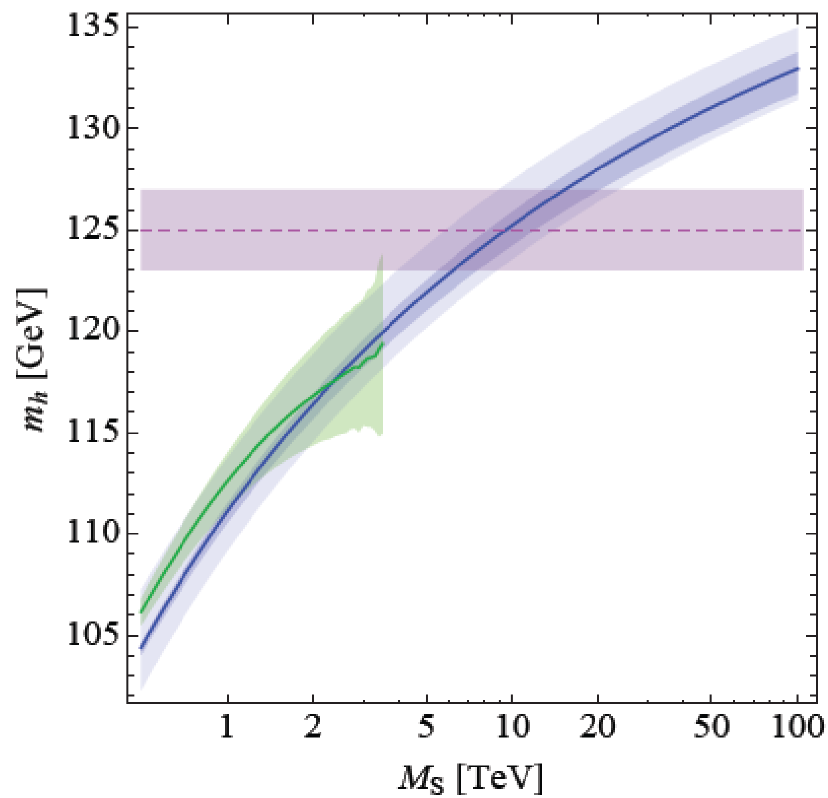
logarithmic dependence
on stop mass

$$m_{\tilde{t}}^2 \sim \begin{pmatrix} m_Q^2 & m_t X_t \\ m_t X_t & m_U^2 \end{pmatrix} \qquad X_t = A_t - \mu\cot\beta, \qquad \mathcal{L} \supset y_t A_t Q \bar{u} H_u + c.c.$$

Motivation

arXiv:1112.3068 by Patrick Draper, Patrick Meade, Matthew Reece, David Shih





In GMSB, messenger scale has to be high so that RG is long enough to generate large A term to get 125 GeV Higgs.

Assuming A terms vanish, one needs stop mass to be 5~10 TeV.

General problem and solution:

Vanilla GMSB generates

- A term at 2 loop,
- squared stop mass at 2 loop.

⟹ Xt/Ms at messenger scale is very small.

125 GeV Higgs requires:

- very high messenger scale with very heavy gluino
- very heavy stop is needed

General problem and solution:

Is there a way to save low scale GMSB while keeping stop mass not too high?

- Modify the model to generate large A term at messenger scale is one option.

- Flavor problem favors to generate A term from Higgs sector.

$$a_u F^{\dagger}_{H_u} H_u + \boxed{a_d F^{\dagger}_{H_d} H_d}$$

→ not important for higgs mass

- μ/Bμ problem is also a long standing problem for GMSB in Higgs sector. Is it correlated with the A term problem?

General problem and solution:

The A_t / m^2_{Hu} problem and its similarity with μ/Bμ problem

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

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

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

If μ and Bμ are generated at the same loop level
then generically μ^2 << Bμ

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

If A_t and m^2_{Hu} are generated at the same loop level
then generically A_t^2 << m^2_{Hu}

A_t / m^2_{Hu} is more difficult since no symmetry forbids m^2_{Hu}

General problem and solution:

Phenomenology requirements:

- 125 GeV Higgs: $A_t \sim m_{stop} \sim$ 1-loop
- viable EWSB vacuum: $\mu \sim \sqrt{B\mu} \sim m_{Hu} \sim$ 1-loop

Effective Kahler potential

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

LO in SUSY breaking:

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

Generic expression for Z's cannot satisfy the phenomenological requirements.

General problem and solution:

Solution:

Minimal gauge mediation is the saver!

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

$U(1)_R$ is assigned as

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

Thus at 1-loop, we have

$$Z^{(1)}_{u,d} = a\lambda^2_{u,d} \log XX^\dagger/\Lambda^2,$$

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

generate A_t at 1 loop
no m^2_{Hu} at 1 loop
module to generate large A_t properly

generate both μ and Bμ at 1 loop
setting λ_d to be zero
by a $U(1)_X$ symmetry

Model I: MSSM with large A term

$$W = X\,\phi_i \cdot \tilde{\phi}_i + \lambda_u\,H_u \cdot \phi_1 \cdot \tilde{\phi}_2 + y_t\,H_u \cdot Q \cdot U + \mu\,H_u \cdot H_d + \ldots$$

$$\Downarrow$$

$$A_t = \boxed{-d_H \frac{\alpha\,\lambda_u}{4\pi}\Lambda}$$ → 1-loop contribution

d_H counts the number of fields coupled to H_u through λ_u

$d_H \sim N_{mess}$

large N_{mess} is helpful to increase Xt/Ms

Model I: MSSM with large A term

$$W = X\,\phi_i \cdot \tilde{\phi}_i + \lambda_u\, H_u \cdot \phi_1 \cdot \tilde{\phi}_2 + y_t\, H_u \cdot Q \cdot U + \mu\, H_u \cdot H_d + \ldots$$

$$\Downarrow$$

$$\delta m^2_{H_u} = -d_H \frac{\alpha_{\lambda_u}}{12\pi} h(\Lambda/M) \left(\frac{\Lambda}{M}\right)^2 \Lambda^2 + \left(d_H (d_H + 3) \frac{\alpha^2_{\lambda_u}}{16\pi^2} - d_H C_r \frac{\alpha_r \alpha_{\lambda_u}}{8\pi^2} \right) \Lambda^2$$

1-loop F/M^2 suppressed contribution
negative
helps to trigger EWSB especially at low messenger scale

2-loop contribution
positive
may cause difficulty for EWSB

2-loop contribution
negative
helps to trigger EWSB especially when messenger fields carry color

Model I: MSSM with large A term

$$W = X\,\phi_i \cdot \tilde{\phi}_i + \lambda_u\,H_u \cdot \phi_1 \cdot \tilde{\phi}_2 + y_t\,H_u \cdot Q \cdot U + \mu\,H_u \cdot H_d + \ldots$$

$\Downarrow$

$$\delta m_Q^2 = -d_H \frac{\alpha_t \alpha_{\lambda_u}}{16\pi^2}\Lambda^2$$
$$\delta m_U^2 = -d_H \frac{\alpha_t \alpha_{\lambda_u}}{8\pi^2}\Lambda^2$$

negative contributions to the stop masses
could induce tachyonic stop

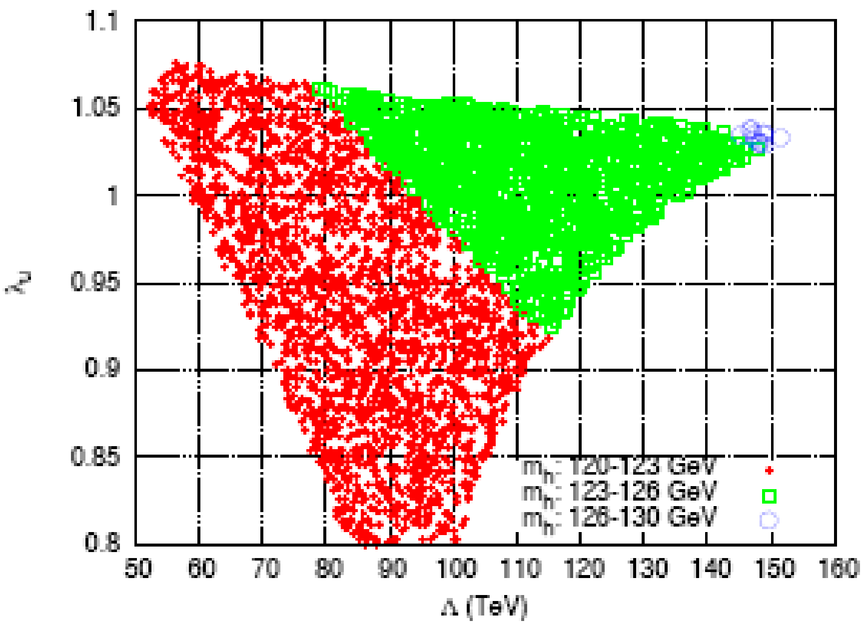
Xt/Ms ~ O(1) $\Rightarrow$ $\alpha_{\lambda_u} \sim \alpha_t$

tachyonic stop problem is not trivial

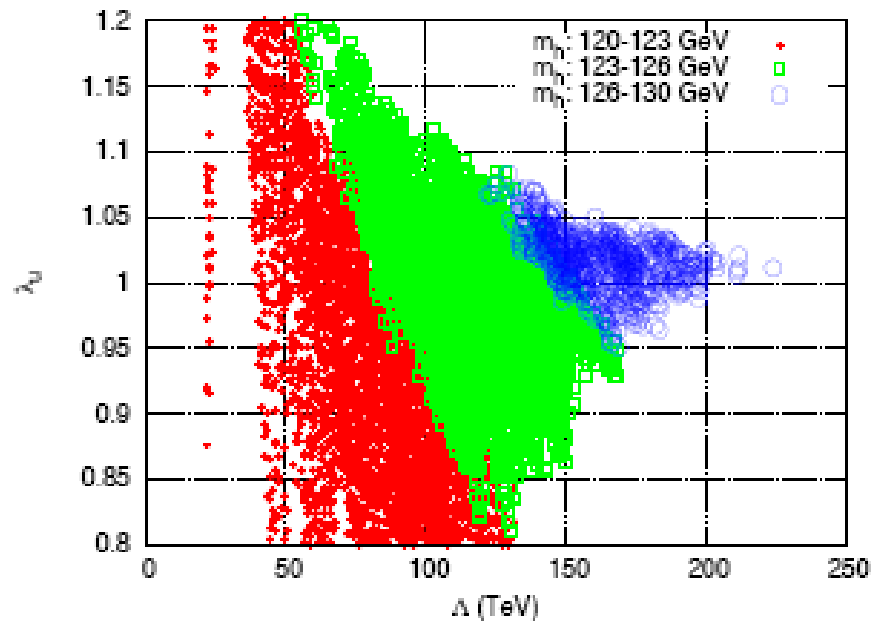
Model I: MSSM with large A term

arXiv:1203.2336 by Kang, Li, Liu, Tong and Yang

$10 + \bar{10}$ messenger, without F/M^2 suppressed 1-loop contribution



messenger scale 10^8 GeV



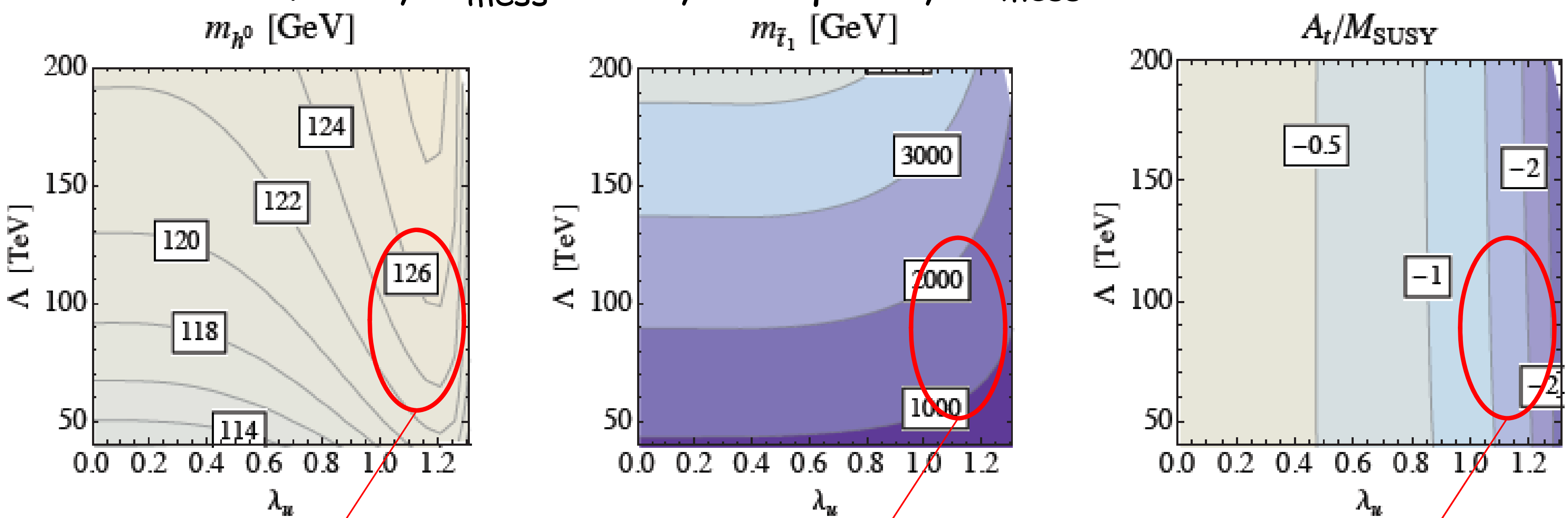
messenger scale 10^{12} GeV

Messenger scale has to be high so that
RG running is long enough to trigger EWSB.

Model I: MSSM with large A term

Including 1-loop contribution, low messenger scale is accessible.

$5 + \bar{5}$ model, $M_{mess} = 2\Lambda$, $\tan\beta = 10$, $N_{mess} = 4$



125 GeV Higgs
can be achieved.

stop mass is
about 1.5 TeV.

max mixing scenario

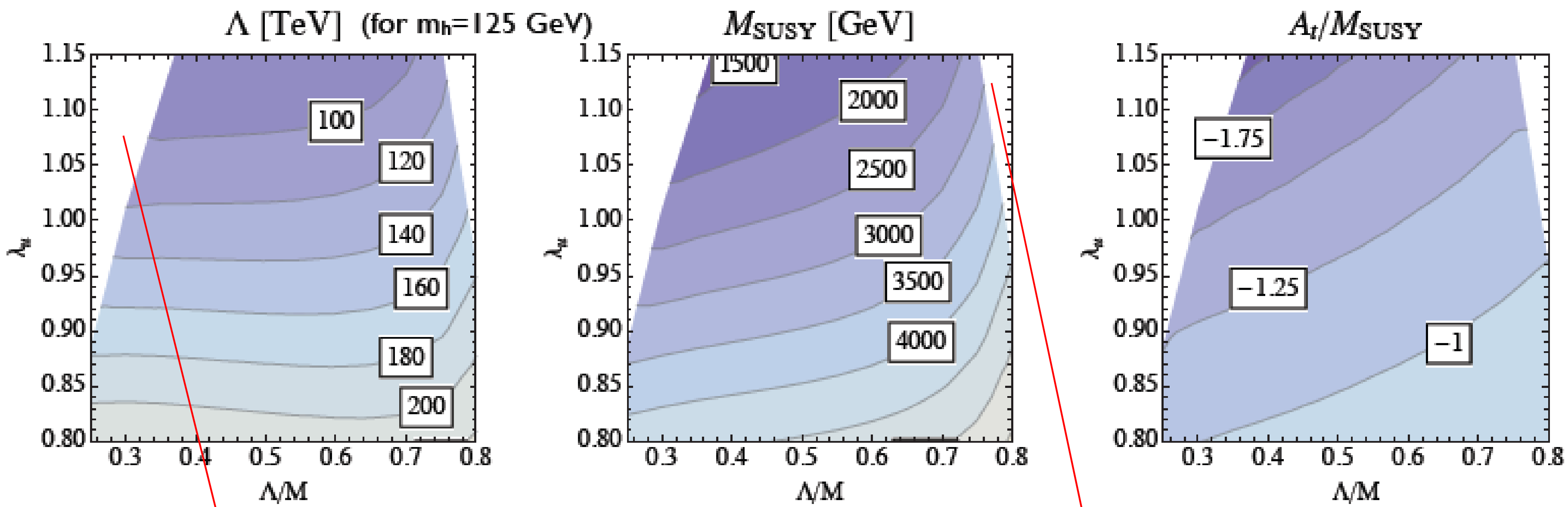
M_{mess} is about 10^5 GeV.

This formalism to generate large A-term
could be attached to the any model of GMSB!

Model I: MSSM with large A term

Requiring Higgs to be 125 GeV:

$5 + \bar{5}$ model, $\tan\beta = 10$, $N_{mess} = 4$



m^2_{Hu} is too negative.

Sleptons are driven tachyonic.

$$16\pi^2 \frac{d}{dt} m^2_{L_3} = X_\tau - 6 g_2^2 |M_2|^2 - \frac{6}{5} g_1^2 |M_1|^2 - \frac{3}{5} g_1^2 S$$

$$S = m^2_{H_u} - m^2_{H_d} + \mathrm{Tr}[\mathbf{m^2_Q} - \mathbf{m^2_L} - 2\mathbf{m^2_{\bar{u}}} + \mathbf{m^2_{\bar{d}}} + \mathbf{m^2_{\bar{e}}}]$$

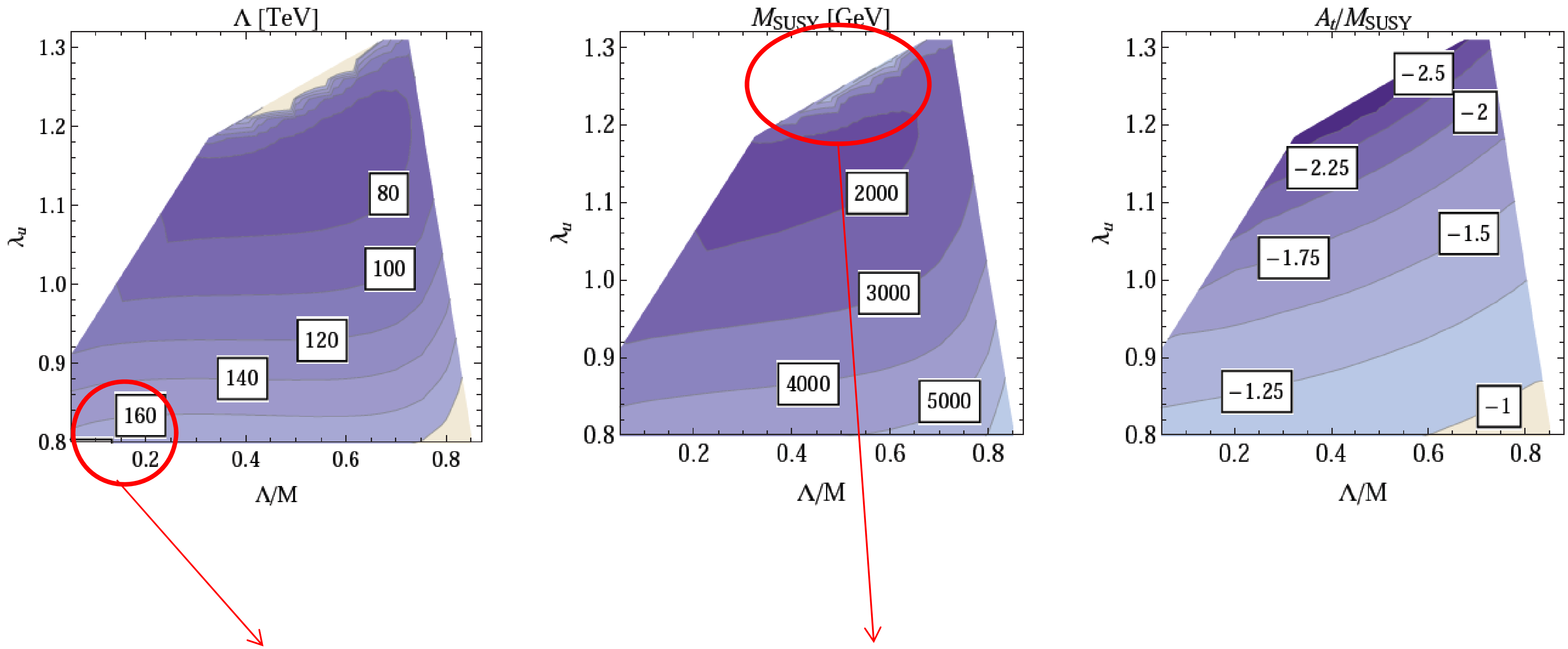
m^2_{Hu} is too positive.

EWSB is not triggered.
Λ/M cannot be too small.

Model I: MSSM with large A term

Requiring Higgs to be 125 GeV:

$10 + \overline{10}$ model, $\tan\beta = 10$, $N_{mess} = 2$



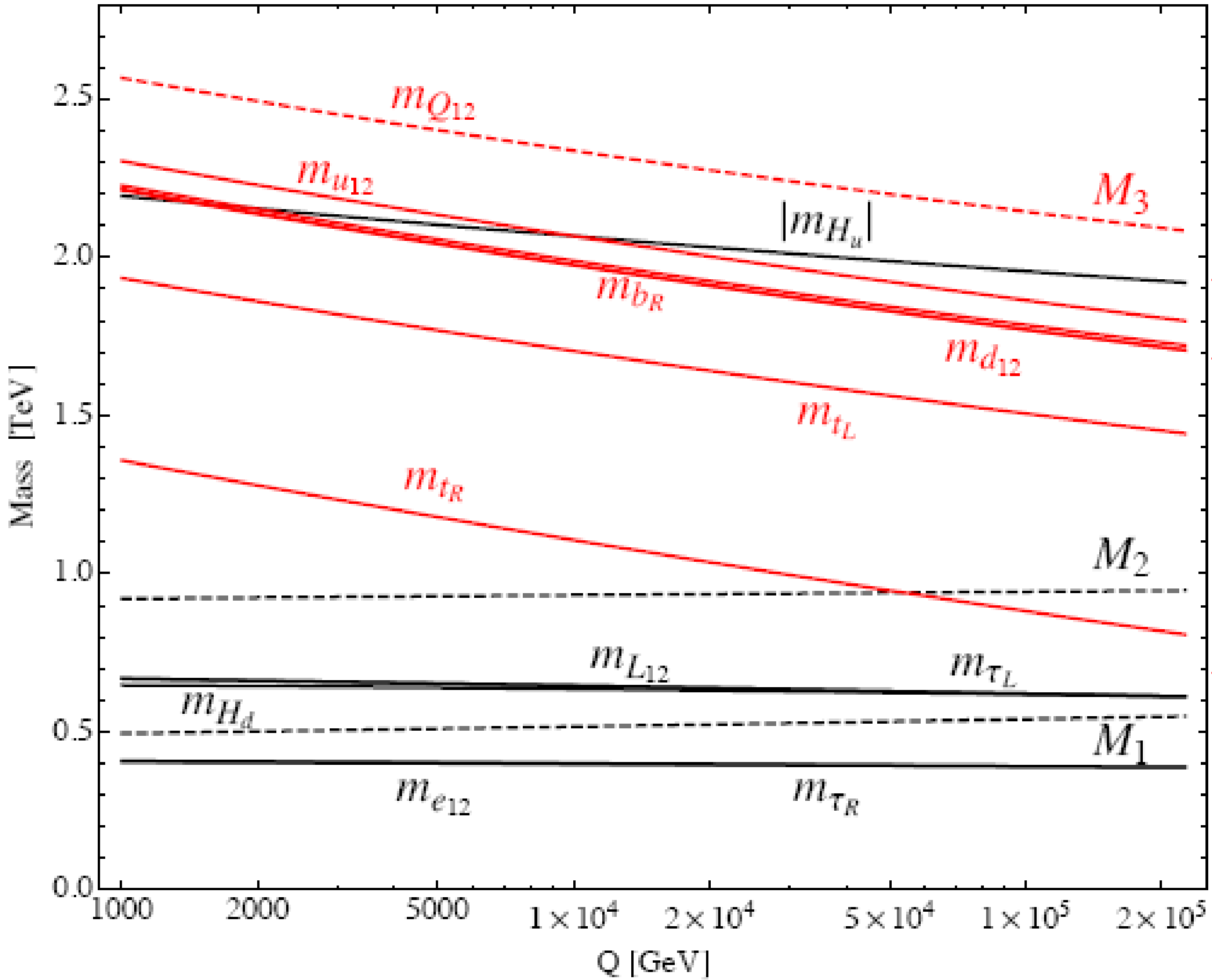
Lower region of Λ/M is open than the previous case since messenger has color now.

Stop becomes tachyonic since λ_u is too large.

Model I: MSSM with large A term

Spectrum: $\Lambda = 110\text{TeV}$ $M_{\text{mess}} = 220\text{TeV}$ $5 + \bar{5}$ model

$\lambda_u = 1.1$ $N_{\text{mess}} = 4$ $\tan\beta = 10$



$m^2_{Hu} < 0$
at messenger scale
Not radiative EWSB

stop mass is
much lower than
other squarks

Model II: NMSSM with large A terms, μ and B μ

- NMSSM provides nice solution for μ and B μ

- If λ and κ are perturbative up to GUT scale, it does not help to increase higgs mass, thus large A_t is preferred.

Previous technique can be attached to NMSSM to generate large A_t .

- NMSSM with GMSB requires large negative m_N^2 for EWSB.

de Gouvea, Friedland, Murayama Phys.Rev.D57:5676-5696,1998
Morrissey, Pierce Phys.Rev.D78:075029,2008

The same technique can be applied to N-messenger-messenger interaction.
Large negative m_N^2 can be generated.
The large negative 1-loop Λ/M suppressed contribution will be important!

Model II: NMSSM with large A terms, μ and B μ

$$W \sim \lambda X \Phi\tilde{\Phi} + \lambda_u H_u \Phi\tilde{\Phi} + \lambda_N N \Phi\tilde{\Phi}$$

Giudice & Rattazzi '97
Delgado, Giudice & Slavich '07

$$W = X(\phi_i \cdot \tilde{\phi}_i + \varphi_i \cdot \tilde{\varphi}_i) + \lambda_u H_u \cdot (\phi_1 \cdot \tilde{\phi}_2 + \varphi_1 \cdot \tilde{\varphi}_2) + \lambda_N N \phi_i \cdot \tilde{\varphi}_i$$
$$+\lambda N H_u \cdot H_d - \frac{1}{3}\kappa N^3 + y_t H_u \cdot Q \cdot U + \ldots$$

i,j are gauge indices.

double the messenger fields to avoid N mixing with X

- Z3: $\mathbb{Z}_3(X, \phi_i, \tilde{\phi}_i, \varphi_i, \tilde{\varphi}_i, H_u, H_d, N) = (0, 1, 2, 2, 1, 0, 2, 1)$
- U(1)x : $q_X(X, \phi, \tilde{\phi}, \varphi, \tilde{\varphi}, H_u, H_d, N) = (1, 0, -1, -1, 0, 1, -1, 0)$

Model II: NMSSM with large A terms, μ and B μ

$$\delta m_{H_u}^2 = \left(d_H \frac{\alpha_{\lambda_N} \alpha_{\lambda_u}}{16\pi^2} - d_N \frac{\alpha_\lambda \alpha_{\lambda_N}}{16\pi^2} \right) \Lambda^2$$

$$\delta m_{H_d}^2 = \left(- d_H \frac{\alpha_\lambda \alpha_{\lambda_u}}{16\pi^2} - d_N \frac{\alpha_\lambda \alpha_{\lambda_N}}{16\pi^2} \right) \Lambda^2$$

extra contributions to soft mass terms of higgs

$$\delta m_Q^2 = \delta m_U^2 = \delta A_t = 0$$

$$m_N^2 = -d_N \frac{\alpha_{\lambda_N}}{12\pi} h(\Lambda/M) \left(\frac{\Lambda}{M} \right)^2 \Lambda^2 + \text{ several two loop terms}$$

Λ/M suppressed 1-loop contribution

$$A_\lambda = -\left(d_H \frac{\alpha_{\lambda_u}}{4\pi} + d_N \frac{\alpha_{\lambda_N}}{4\pi} \right) \Lambda$$

$$A_\kappa = -3 d_N \frac{\alpha_{\lambda_N}}{4\pi} \Lambda$$

induce 1-loop contributions to A terms

similar story as Hu

Model II: NMSSM with large A terms, μ and B μ

- Three extra parameters comparing with MSSM

  (λ, κ, λ_N)

  Bμ is not independent any more.

  One more minimization equation.

  ⇨ Only one extra input parameter, chosen as λ.

- Large higgs mass from stop mixing, μ and Bμ from NMSSM

  ⇨ Take λ to be small.

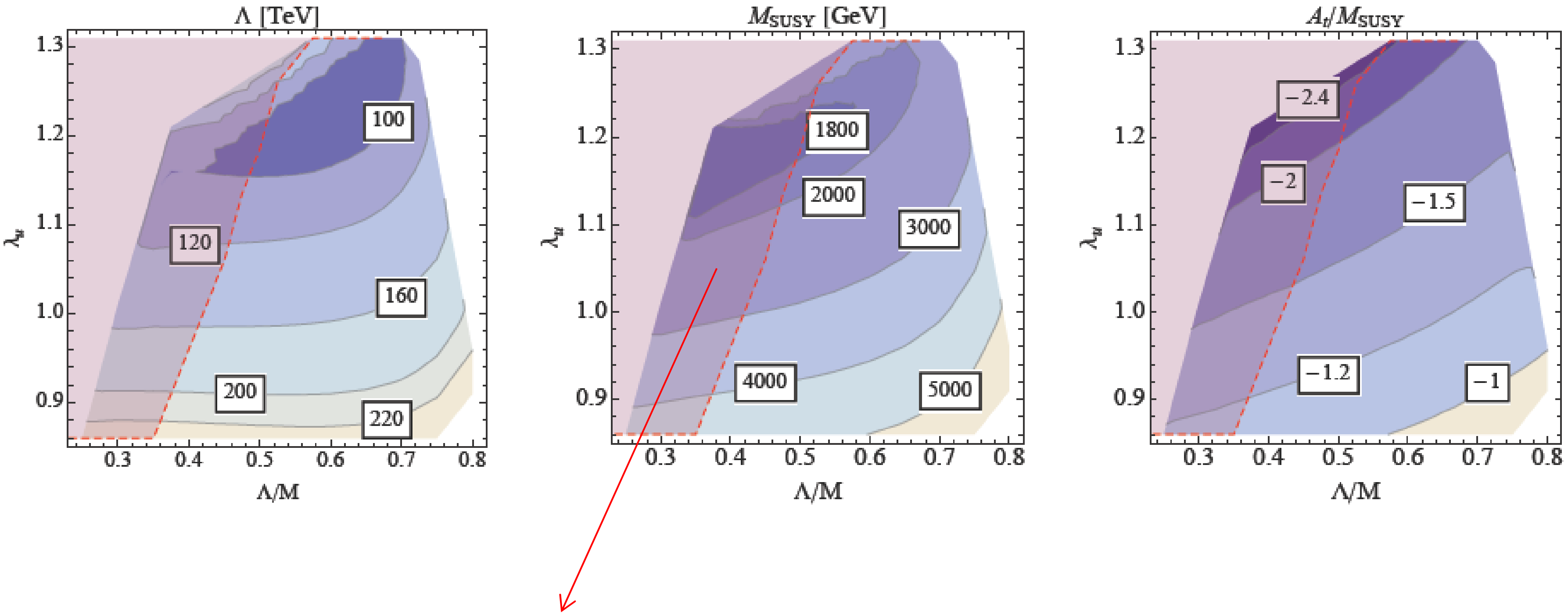
  Singlet sector almost decouples.

  No large effects to MSSM sector.

Model II: NMSSM with large A terms, μ and B μ

Requiring Higgs to be 125 GeV:

$5 + \bar{5}$ model, $\tan\beta = 10$, $N_{mess} = 4$

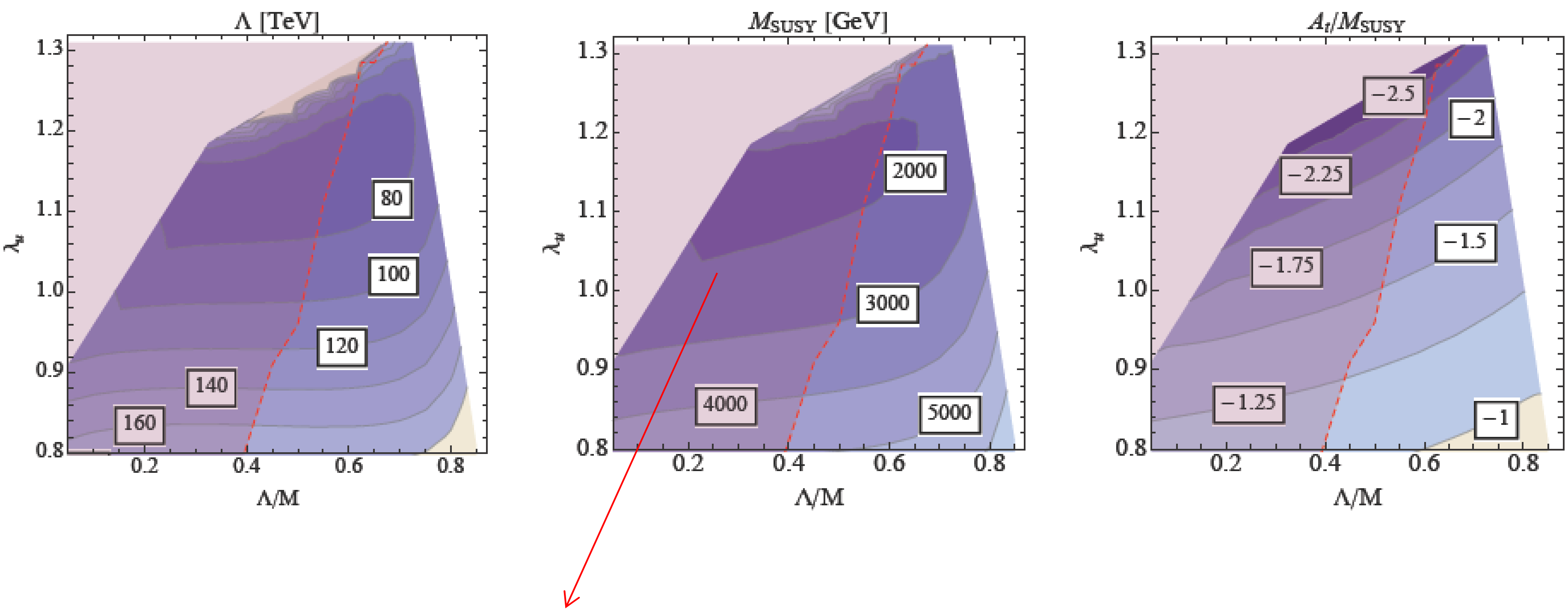


Do not have a consistent solution with small λ.
Further constrains the parameter space.

Model II: NMSSM with large A terms, μ and B μ

Requiring Higgs to be 125 GeV:

$10 + \overline{10}$ model, tan β =10, N_{mess} =2



Do not have a consistent solution with small λ.
Further constrains the parameter space.

Phenomenology:

- Large splitting between stop and other squarks
  due to extra large two loop contributions
  Stop mass is generically larger than 1.5 TeV

- Sleptons, wino and bino are below 1 TeV

- Stau is generically NLSP
  NLSP decays within detector since F is low.
  Multilepton search would be powerful.

- Higgs is SM-like
  since both λ and κ are small

Landau poles:

- No Landau poles for NMSSM couplings up to GUT scale if

$N_{mess} \leq 6$ for $5 + \bar{5}$ model
$N_{mess} \leq 2$ for $10 + \overline{10}$ model

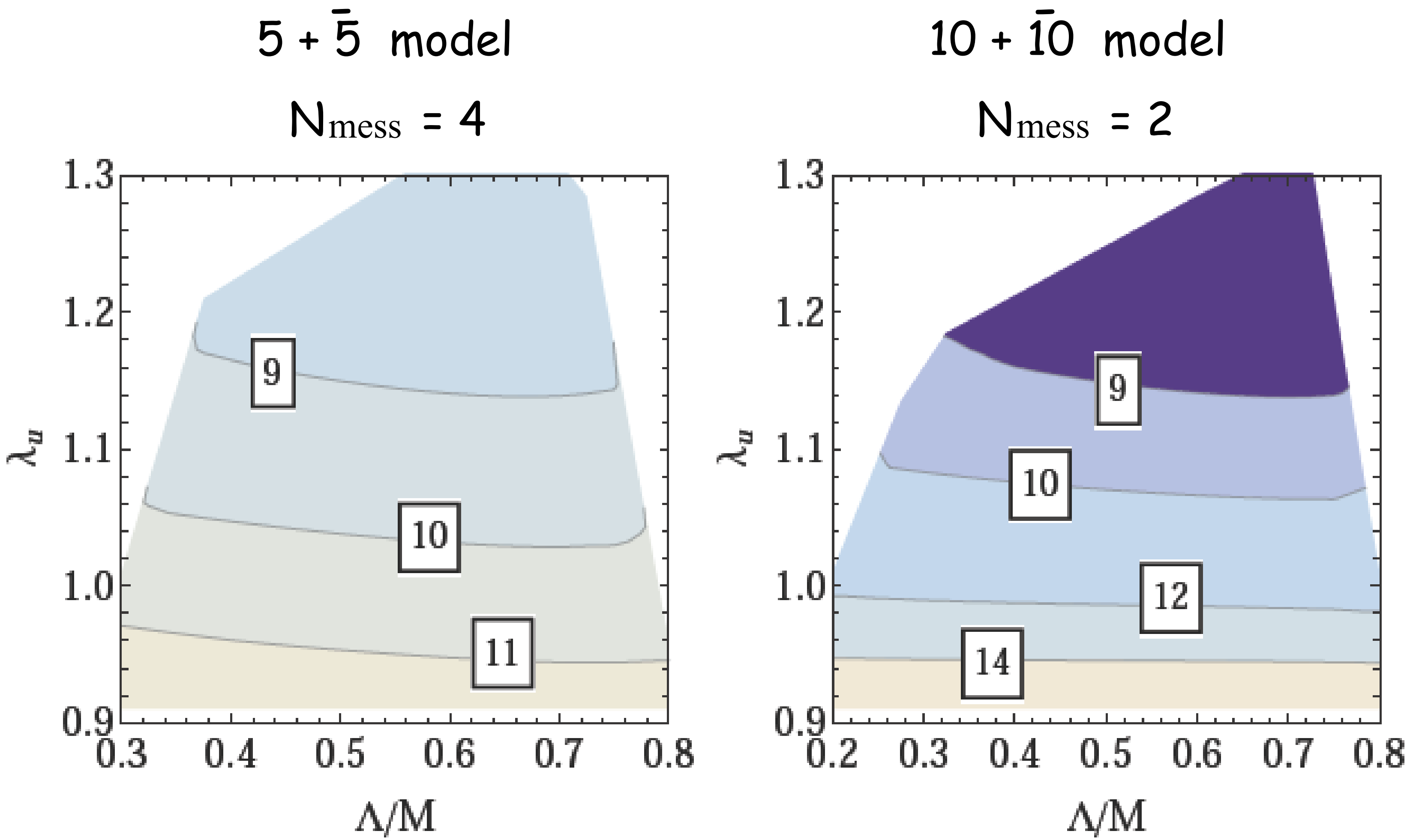
- λ_u may blow up before GUT scale.

$$\beta_{\lambda_u} \sim \frac{\lambda_u}{16\pi^2}\left[(N_{mess}+3)\lambda_u^2 + 3y_t^2 + \ldots\right] \qquad (\mathbf{5} \oplus \overline{\mathbf{5}} \text{ messengers})$$

$$\beta_{\lambda_u} \sim \frac{\lambda_u}{16\pi^2}\left[(3N_{mess}+3)\lambda_u^2 + 3y_t^2 - \frac{16}{3}g_3^2 + \ldots\right] \qquad (\mathbf{10} \oplus \overline{\mathbf{10}} \text{ messengers})$$

help to control
the running

Landau poles:



Scale for new physics to enter!

Summary:

- General difficulties to have a 125 GeV higgs in GMSB

- A complete module of weakly-coupled messengers to solve the problem.

- This module can be attached to NMSSM to deal with the μ/Bμ problem.

  Large negative m_N^2 is generated by the same technique!

- Interesting features of the model:

  - low messenger scale
  - stop significantly lighter than other squarks
  - EWSB at messenger scale, not radiative
  - SM-like higgs sector

Backup slides:

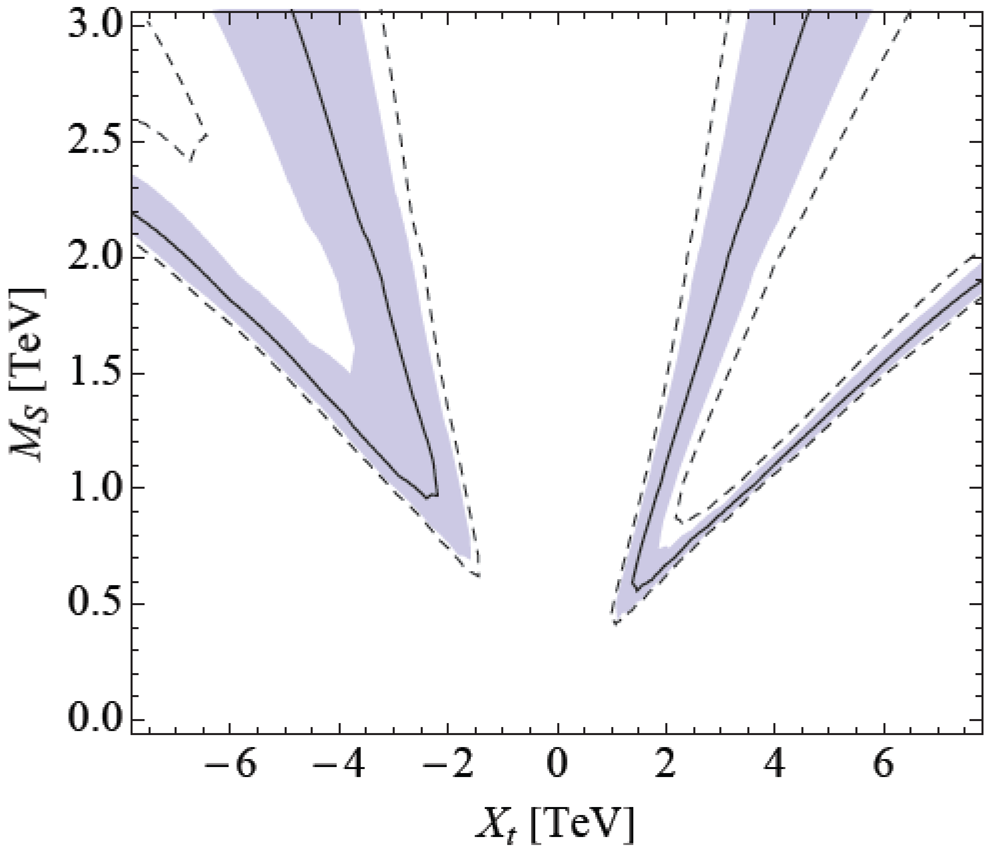
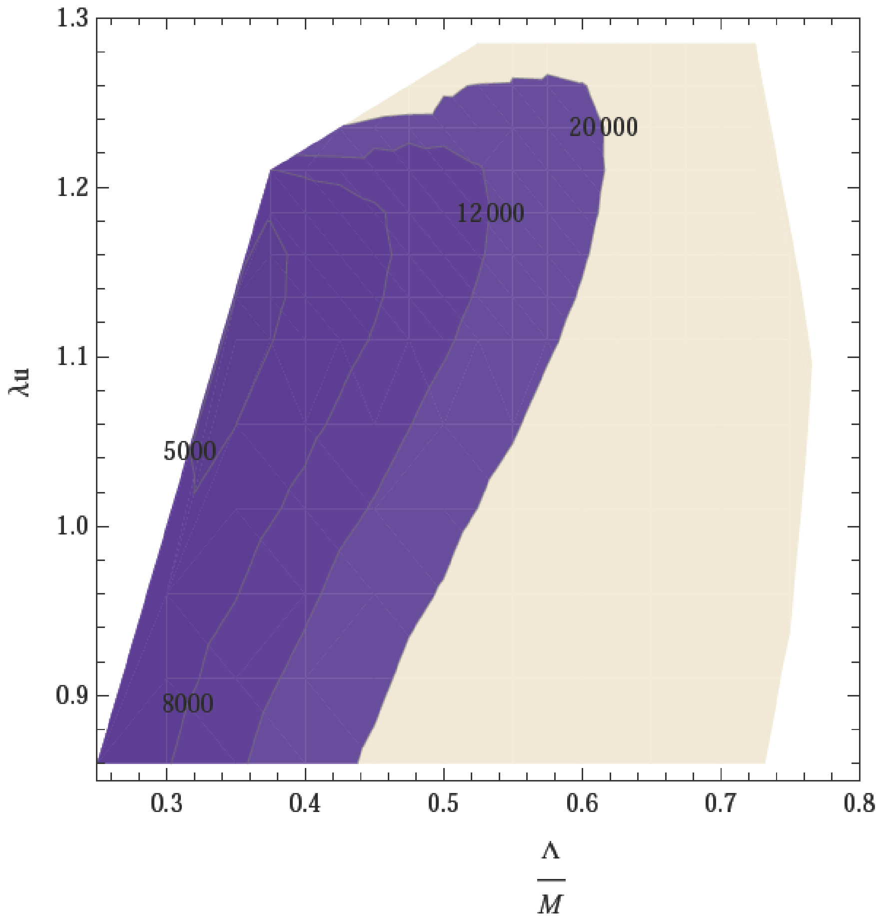


FIG. 2. Contours of constant m_h in the M_S vs. X_t plane, with $\tan\beta = 30$ and $m_Q = m_U$. The solid/dashed lines and gray bands are as in fig. 1.

Fine tuning:

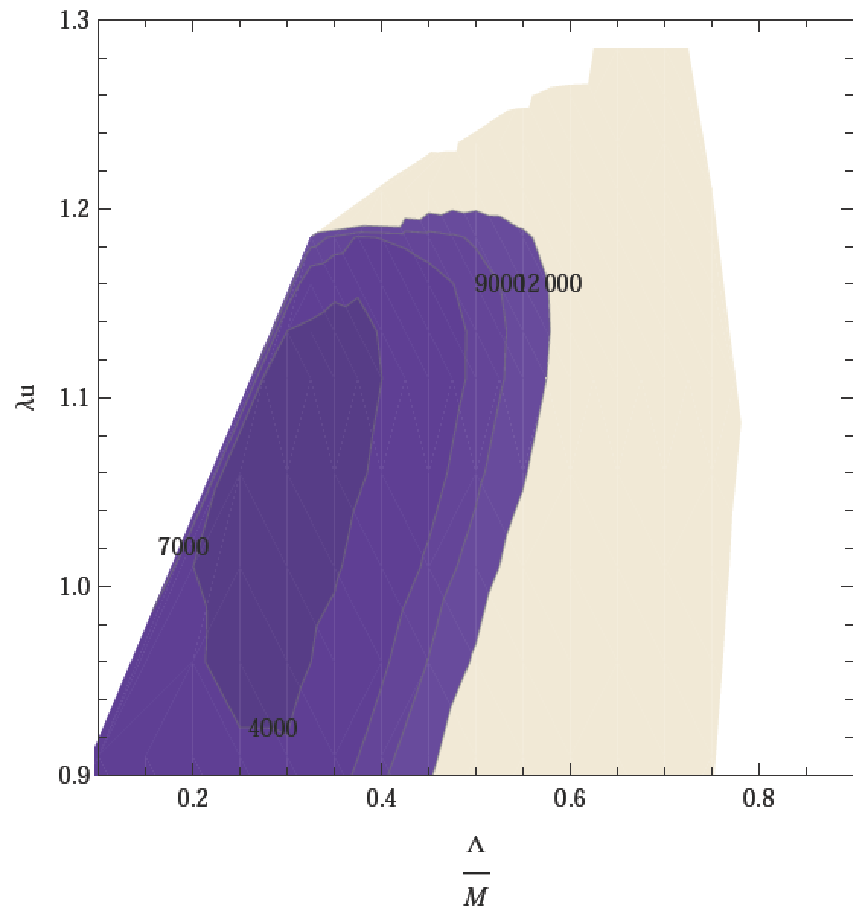
$5 + \bar{5}$ model

$N_{mess} = 4$

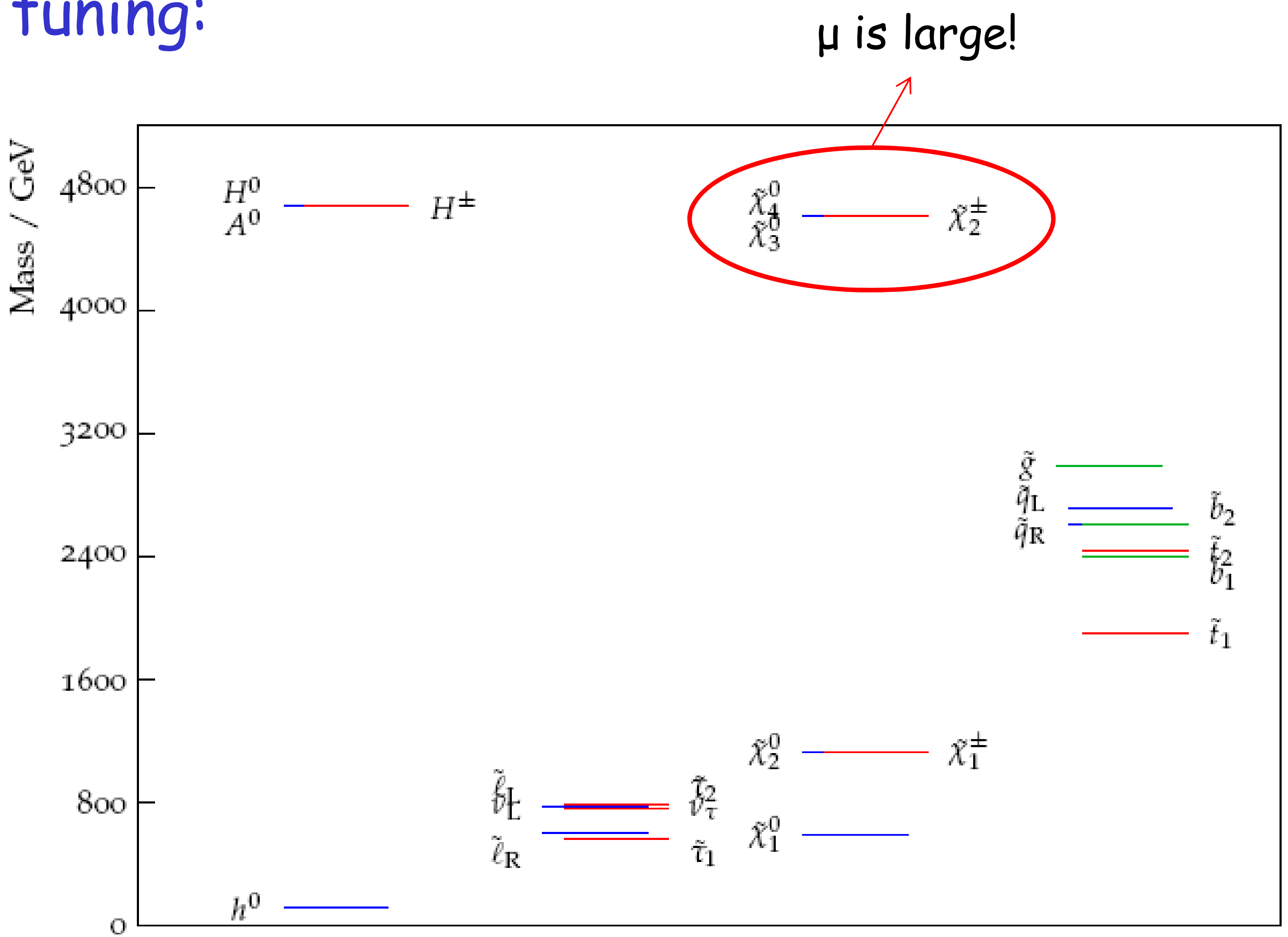


$10 + \bar{10}$ model

$N_{mess} = 2$



Fine tuning:



$5+\bar{5}$ model, $M_{mess} = 2\,\Lambda$, $\lambda_u = 1.1$
$\tan\beta = 10$, $N_{mess} = 4$, $\Lambda = 110$ TeV