Surveying Models for Maximal Stop Mixing

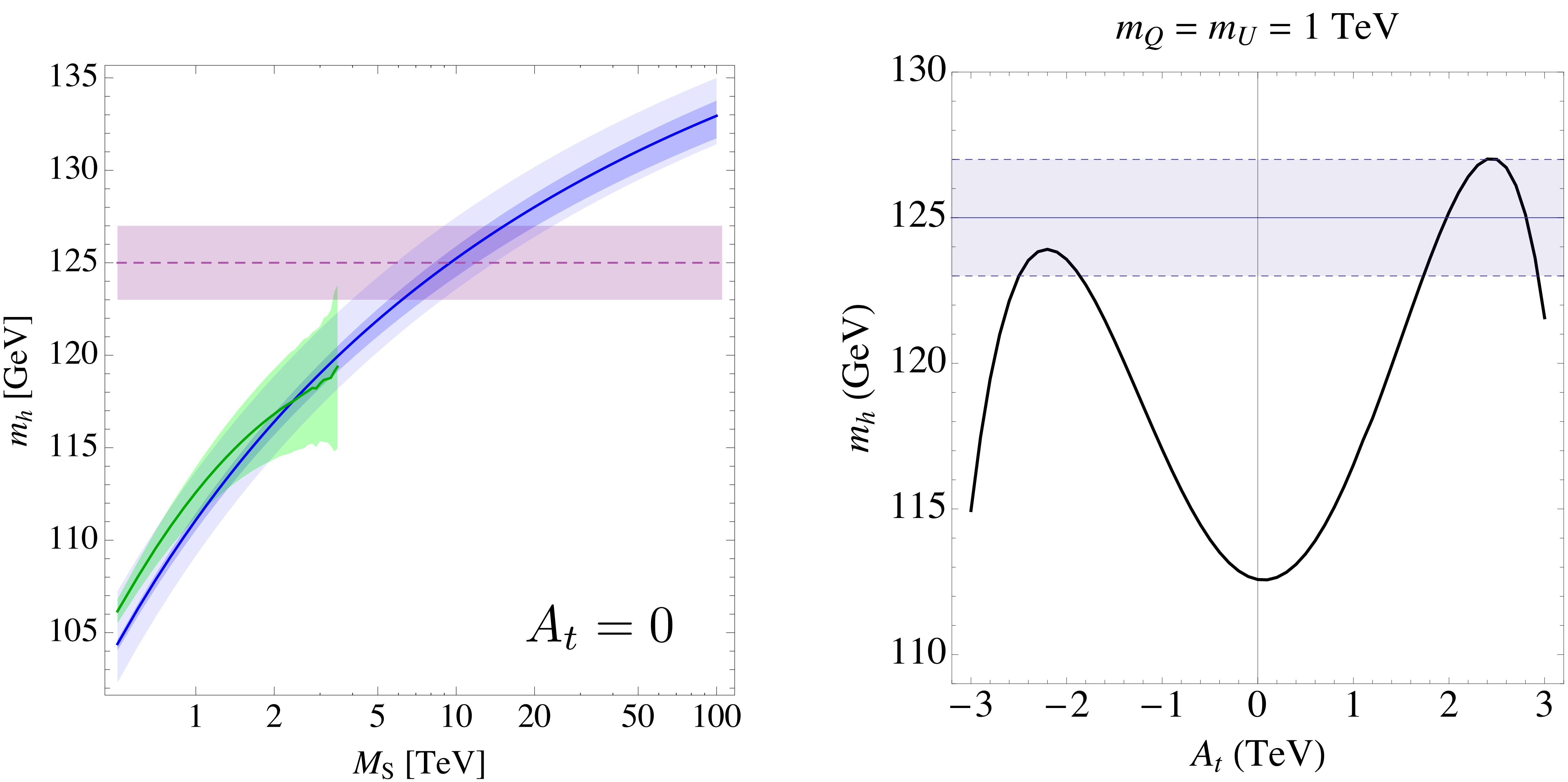
David Shih

Based on:

Draper, Meade, Reece & DS (1112.3068)
Craig, Knapen, DS & Zhao (1206.4086)
Craig, Knapen & DS (1302.2642)
Evans & DS (1303.0228)

Higgs@125 and SUSY

The discovery of the Higgs at 125 GeV has profound implications for SUSY and naturalness.



Draper, Meade, Reece & DS

Higgs@125 and SUSY

MSSM

- $m_h \leq m_Z$ at tree-level. Need large radiative corrections from stops to lift m_h to 125 GeV.
- TeV-scale stops require large A-terms (“maximal mixing”).
- Fine-tuning is at the percent level or worse.

Beyond the MSSM

- Boost the Higgs mass with additional matter and interactions (singlets, extra gauge groups, ...)
- This can alleviate the fine tuning problem, but it usually introduces its own complications (Landau poles, unification, mu problems...)

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Can build complete models with detailed predictions for the LHC.

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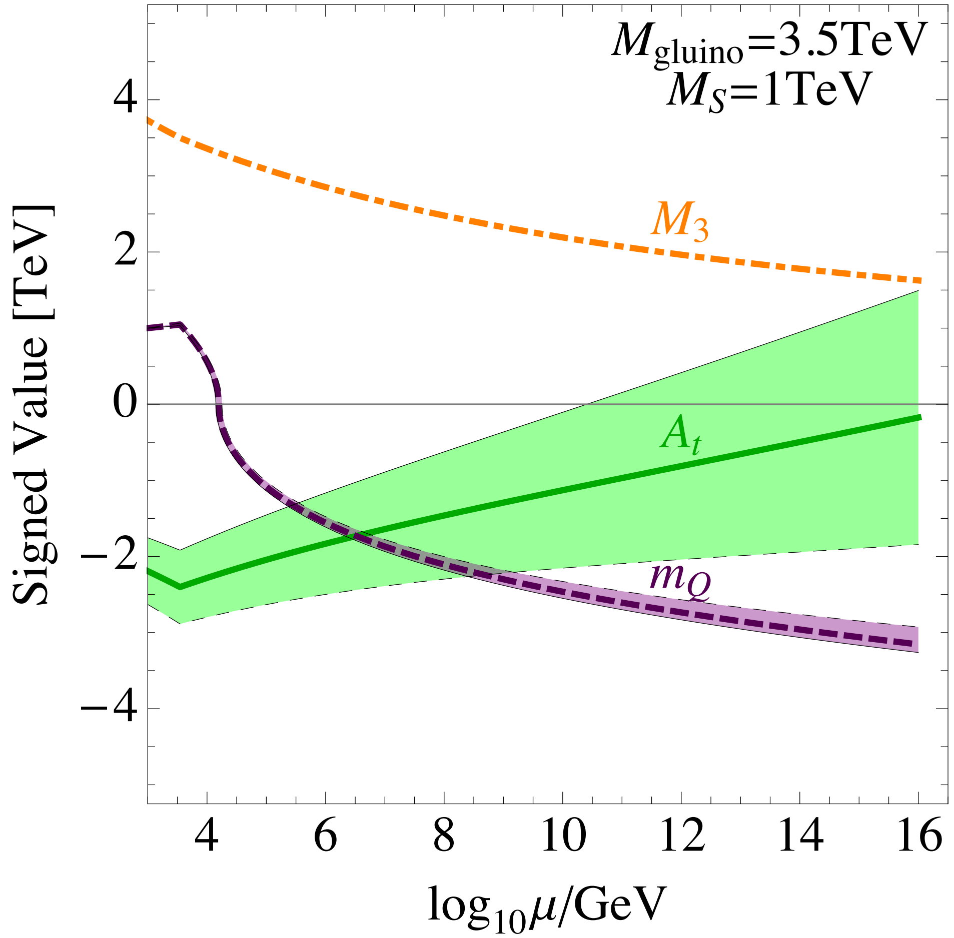
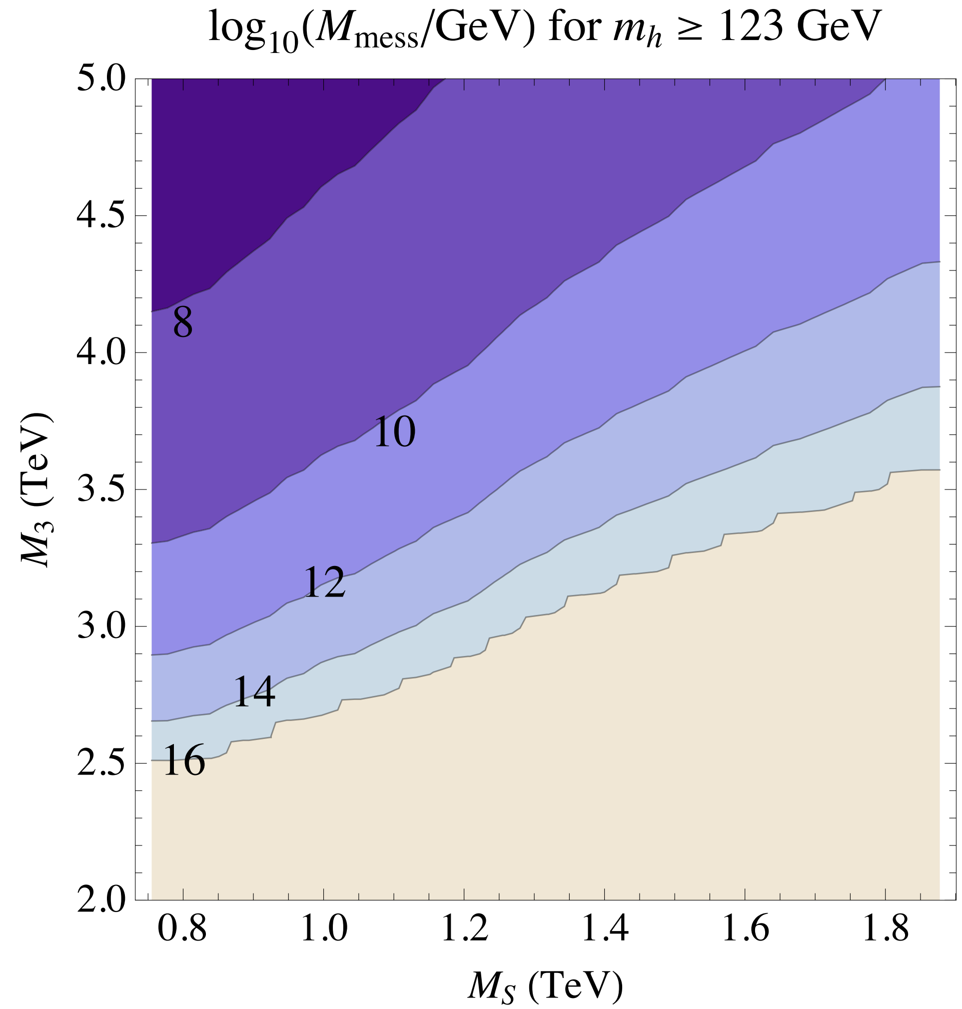
Can focus on the question: how to generate large weak-scale A-terms?

A-terms through RG

- Large weak-scale A-terms can arise through the RG.
- This is a highly constrained scenario. Requires $M_3 \gtrsim 3$ TeV and $M_{mess} \gtrsim 10^8$ GeV.

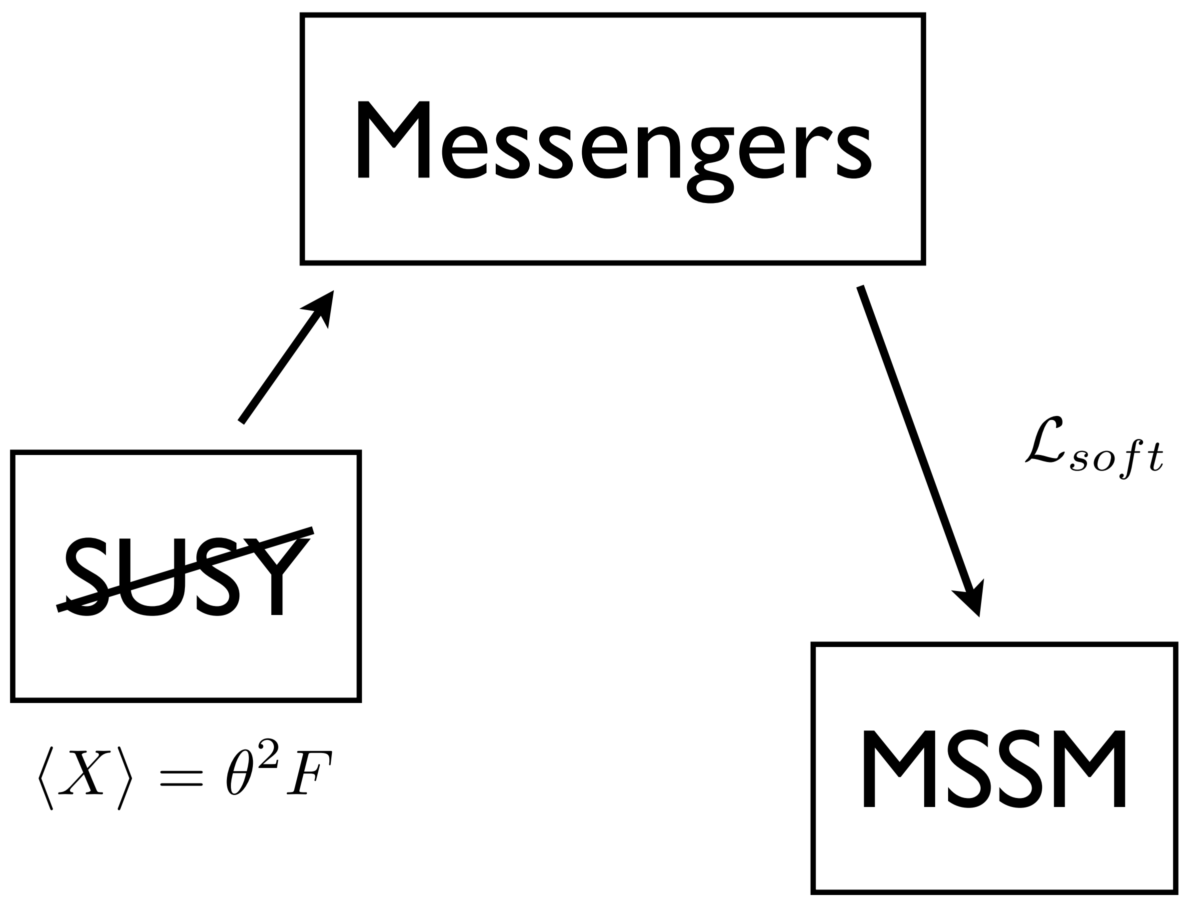




(Draper, Meade, Reece, DS)

A-terms through Messengers

- A-terms can also arise through MSSM/messenger interactions.



$\langle X \rangle = \theta^2 F$

$$\mathcal{L}_{soft} = \int d^4\theta \frac{X^\dagger X}{M^2} Q^\dagger Q + \ldots$$
$$= m_Q^2 Q^\dagger Q + \ldots$$

- Gauge interactions not enough, need direct couplings, e.g.

$$W = \sum_{Q \in MSSM} \lambda Q \mathcal{O}_Q + \ldots$$

A-terms are Bilinear Couplings

- The A-terms generally arise as bilinear couplings:

$$\mathcal{L} \supset \int d^4\theta \, \frac{X}{M} \left(c_{Qij} Q_i^\dagger Q_j + c_{Uij} U_i^\dagger U_j + H_u^\dagger H_u + \ldots \right)$$
$$\supset A_{Qij} F_{Q_i}^\dagger Q_j + A_{Uij} F_{U_i}^\dagger U_j + A_{H_u} F_{H_u}^\dagger H_u + \ldots$$

- After integrating out the auxiliary fields, these become the usual trilinear A-terms:

$$\mathcal{L} \supset A_{Qij} \lambda_{ik}^u H_u U_k Q_j + A_{Uij} \lambda_{ki}^u H_u Q_k U_j + A_{H_u} \lambda_{ij}^u H_u Q_i U_j + \ldots$$

- Higgs-type A-terms are automatically MFV; the squark-type A-terms are not.

An obstacle to large A-terms

- Problem: the effective operators for A-terms and for mass-squareds are very similar.

$$c_{A_Q} \int d^4\theta \, \frac{X}{M} Q^\dagger Q \qquad \text{vs.} \qquad c_{m_Q^2} \int d^4\theta \, \frac{X^\dagger X}{M^2} Q^\dagger Q$$

- So they tend to be generated at the same loop order, implying:

$$m_Q^2 \gg A_Q^2$$

- This is disastrous for EWSB and/or naturalness!

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"The A/m^2 problem"

(Craig, Knapen, DS & Zhao)

Analogy with μ/Bμ

- The A/m^2 problem is completely analogous to the more well-known μ/Bμ problem.
- The operators for μ and Bμ also only differ by one power of X:

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

- Before the Higgs was discovered at 125 GeV, we were not forced to confront the A/m^2 problem.
- Now it is on the same footing as the μ/Bμ problem!

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- Unlike $B\mu$, m^2 is neutral under all symmetries. So one cannot solve the A/m^2 problem by imposing a global symmetry.

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- Even if one solves the A/m^2 problem, a residual problem remains: integrating out the auxiliary fields produces a large, positive contribution to m^2

$$F_Q^\dagger F_Q + A_Q F_Q^\dagger Q + c.c. \quad \rightarrow \quad \delta m_Q^2 = +A_Q^2$$

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  - For Higgs A-terms, this presents problems for radiative EWSB (because $A_t \sim m_{stop}$) and greatly exacerbates fine tuning.
  - For squark A-terms, there is no problem with EWSB, and fine-tuning is not as bad. (Evans & DS)

Classifying the models

<table>
<tr><th>~~SUSY~~ \ Mess</th><th>Weak</th><th>Strong</th></tr>
<tr><td>Weak</td><td>Fully calculable.
Must be MGM</td><td rowspan="2">Incalculable?
No loop factor, no problem?</td></tr>
<tr><td>Strong</td><td>Partially calculable.
Hidden-sector sequestering?</td></tr>
</table>

Weakly-coupled models

$$W = W_{mess} + W_{int} = \left(\kappa_{ij} X \Phi_i \tilde{\Phi}_j + m_{ij} \Phi_i \Phi_j\right) + \lambda_{ij} Q \Phi_i \Phi_j + \ldots$$

$$(Q = Q_{L3}, U_{R3}, H_u)$$

- Weakly-coupled messengers + spurion SUSY-breaking: messengers must be MGM-type!! (Craig, Knapen, DS & Zhao)

$$m_{ij} = 0 \text{ with } \langle X \rangle = M + \theta^2 F$$

- However, the little A/m^2 problem cannot be avoided.

- We recently classified and surveyed all models consistent with perturbative SU(5) unification (Evans & DS).

#	Coupling	$\lvert\Delta b\rvert$	Best Point $\{\frac{\Lambda}{M}, \lambda\}$	$\lvert A_t\rvert / M_S$	$M_{\tilde{g}}$	M_S	$\lvert\mu\rvert$	Tuning
I.1	$H_u\phi_{\overline{5},L}\phi_{1,S}$	N_m	$\{0.375, 1.075\}$	1.98	3222	1842	777	3400
I.2	$H_u\phi_{10,Q}\phi_{10,U}$	$3N_m$	$\{0.25, 1.075\}$	1.99	3178	1828	789	2450
I.3	$H_u\phi_{5,\overline{D}}\phi_{\overline{10},\overline{Q}}$	4	$\{0.25, 1.3\}$	2.05	2899	1709	668	3200
I.4	$H_u\phi_{5,\overline{L}}\phi_{\overline{10},\overline{E}}$	4	$\{0.125, 0.95\}$	0.58	11134	8993	2264	4050
I.5	$H_u\phi_{\overline{5},L}\phi_{24,S}$	6	$\{0.225, 1.000\}$	0.54	13290	9785	3408	3850
I.6	$H_u\phi_{\overline{5},L}\phi_{24,W}$	6	$\{0.15, 1.025\}$	0.67	11835	8637	3259	3410
I.7	$H_u\phi_{\overline{5},D}\phi_{24,X}$	6	$\{0.3, 1.425\}$	2.04	3020	1743	576	3500
I.8	$Q\phi_{\overline{10},\overline{Q}}\phi_{1,S}$	$3N_m$	$\{0.534, 1.5\}$	2.82	4336	1274	2056	1015
I.9	$Q\phi_{5,D}\phi_{\overline{5},L}$	N_m	$\{0.353, 0.858\}$	2.67	4247	1342	2058	1015
I.10	$Q\phi_{10,U}\phi_{5,H_u}$	4	$\{0.51, 1.788\}$	2.65	4040	1318	2301	1275
I.11	$Q\phi_{10,Q}\phi_{5,\overline{D}}$	4	$\{0.378, 1.245\}$	2.76	4020	1257	2292	1260
I.12	$U\phi_{\overline{10},\overline{U}}\phi_{1,S}$	$3N_m$	$\{0.476, 1.622\}$	2.62	3815	1347	2070	1030
I.13	$U\phi_{5,D}\phi_{\overline{5},D}$	$2N_m$	$\{0.301, 0.908\}$	2.91	3829	1199	2061	1020
I.14	$U\phi_{10,Q}\phi_{5,H_u}$	4	$\{0.37, 1.352\}$	2.81	3575	1220	2312	1285
I.15	$U\phi_{10,E}\phi_{5,\overline{D}}$	4	$\{0.51, 1.972\}$	2.63	3526	1312	2310	1280
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II.6	$QQ\phi_{5,\overline{D}}$	1	$\{0.45, 0.1\}$	0.22	7943	9870	3610	5000
II.7	$UD\phi_{\overline{5},D}$	1	$\{0.21, 1.26\}$	2.34	1374	1334	2998	2150
II.8	$QL\phi_{\overline{5},D}$	1	$\{0.14, 1.2\}$	1.51	1501	1204	2203	3700
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II.11	$H_uL\phi_{1,S}$	1^*	$\{0.15, 0.675\}$	0.54	7103	8166	3714	4930
II.12	$H_uL\phi_{24,S}$	5	$\{0.296, 0.96\}$	0.53	12629	9660	3333	3780
II.13	$H_uL\phi_{24,W}$	5	$\{0.212, 0.96\}$	0.65	11487	8710	3687	3380
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Table 1. All possible marginal MSSM-messenger couplings compatible with a perturbative $SU(5)$ framework are tabulated here. The point with the least tuning in each model is also presented. The tuning measure used is defined in (3.7) and is discussed more in Appendix B. Additionally, the values of $\lvert A_t\rvert / M_S$, $M_{\tilde{g}}$, M_S and $\lvert\mu\rvert$ at this least tuned point are shown. Models with $\lvert A_t\rvert / M_S < 1$ rely on heavy stops as opposed to mixed stops. Models II.11-13 generate large neutrino masses. Models II.14-16 possess a $\mu/B\mu$ problem. In the third column, $\lvert\Delta b\rvert$ refers to the messenger contribution to the $SU(5)$ beta function. As the singlet does not contribute to GMSB, models II.11 and II.14 are assigned an additional $\phi_5 \oplus \phi_{\overline{5}}$.

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I.1	$H_u\phi_{\overline{5},L}\phi_{1,S}$	N_m	$\{0.375, 1.075\}$	1.98	3222	1842	777	3400
I.2	$H_u\phi_{10,Q}\phi_{10,U}$	$3N_m$	$\{0.25, 1.075\}$	1.99	3178	1828	789	2450
I.3	$H_u\phi_{5,\overline{D}}\phi_{\overline{10},\overline{Q}}$	4	$\{0.25, 1.3\}$	2.05	2899	1709	668	3200
I.4	$H_u\phi_{5,\overline{L}}\phi_{\overline{10},\overline{E}}$	4	$\{0.125, 0.95\}$	0.58	11134	8993	2264	4050
I.5	$H_u\phi_{\overline{5},L}\phi_{24,S}$	6	$\{0.225, 1.000\}$	0.54	13290	9785	3408	3850
I.6	$H_u\phi_{\overline{5},L}\phi_{24,W}$	6	$\{0.15, 1.025\}$	0.67	11835	8637	3259	3410
I.7	$H_u\phi_{\overline{5},D}\phi_{24,X}$	6	$\{0.3, 1.425\}$	2.04	3020	1743	576	3500
I.8	$Q\phi_{\overline{10},\overline{Q}}\phi_{1,S}$	$3N_m$	$\{0.534, 1.5\}$	2.82	4336	1274	2056	1015
I.9	$Q\phi_{\overline{5},D}\phi_{\overline{5},L}$	N_m	$\{0.353, 0.858\}$	2.67	4247	1342	2058	1015
I.10	$Q\phi_{10,U}\phi_{5,H_u}$	4	$\{0.51, 1.788\}$	2.65	4040	1318	2301	1275
I.11	$Q\phi_{10,Q}\phi_{5,\overline{D}}$	4	$\{0.378, 1.245\}$	2.76	4020	1257	2292	1260
I.12	$U\phi_{\overline{10},\overline{U}}\phi_{1,S}$	$3N_m$	$\{0.476, 1.622\}$	2.62	3815	1347	2070	1030
I.13	$U\phi_{\overline{5},D}\phi_{\overline{5},D}$	$2N_m$	$\{0.301, 0.908\}$	2.91	3829	1199	2061	1020
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I.15	$U\phi_{10,E}\phi_{5,\overline{D}}$	4	$\{0.51, 1.972\}$	2.63	3526	1312	2310	1280
II.1	$QU\phi_{5,H_u}$	1	$\{0.55, 1.64\}$	2.02	769	1965	2738	1800
II.2	$UH_u\phi_{10,Q}$	3	$\{0.009, 1.067\}$	2.14	2203	1628	543	850
II.3	$QH_u\phi_{10,U}$	3	$\{0.269, 1.05\}$	2.27	2514	1458	439	1500
II.4	$QD\phi_{\overline{5},H_d}$	1	$\{0.37, 1.2\}$	1.78	2597	1829	3553	3020
II.5	$QH_d\phi_{\overline{5},D}$	1	$\{0.15, 1.19\}$	1.45	2497	2108	3773	6050
II.6	$QQ\phi_{5,\overline{D}}$	1	$\{0.45, 0.1\}$	0.22	7943	9870	3610	5000
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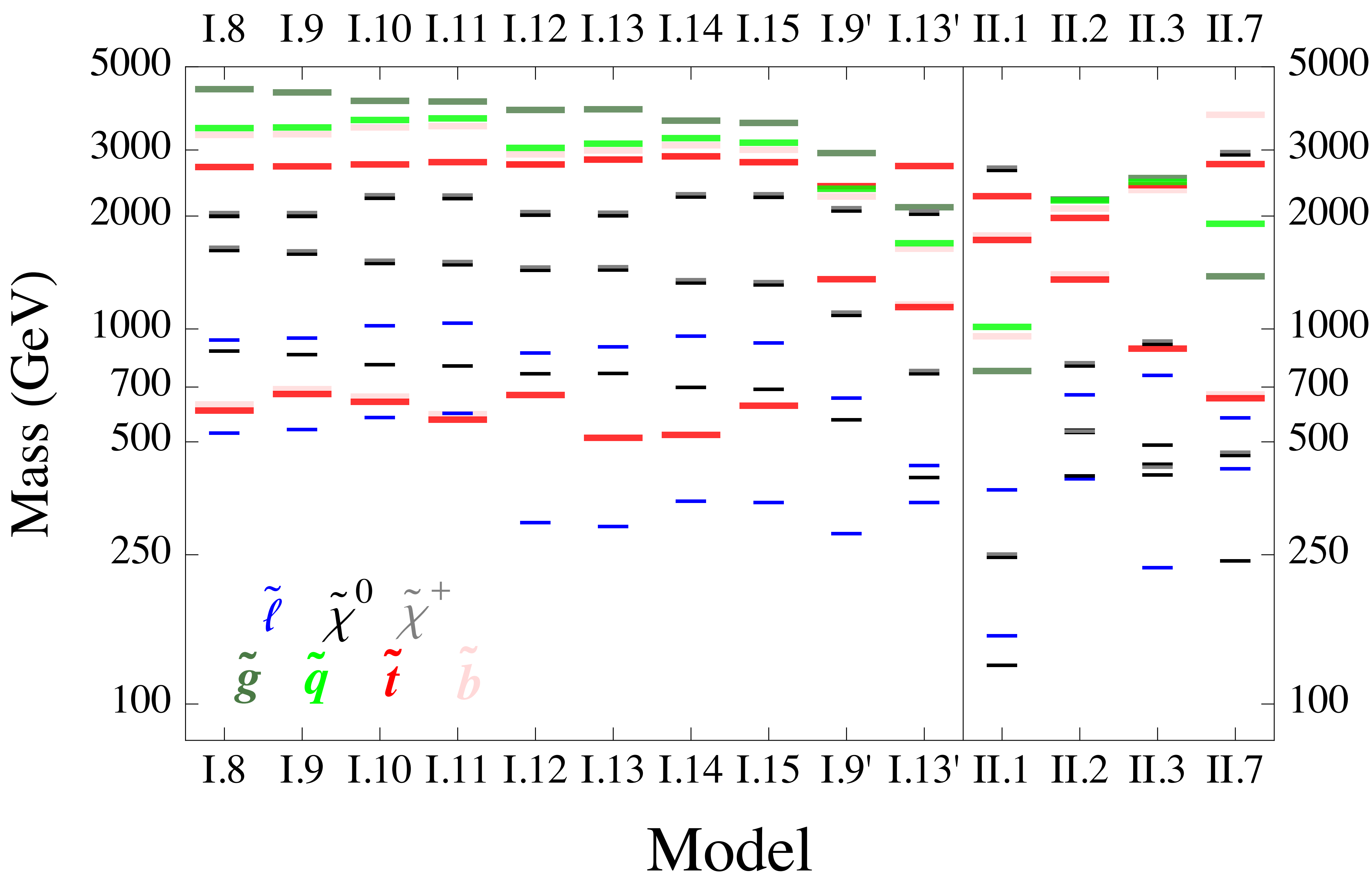
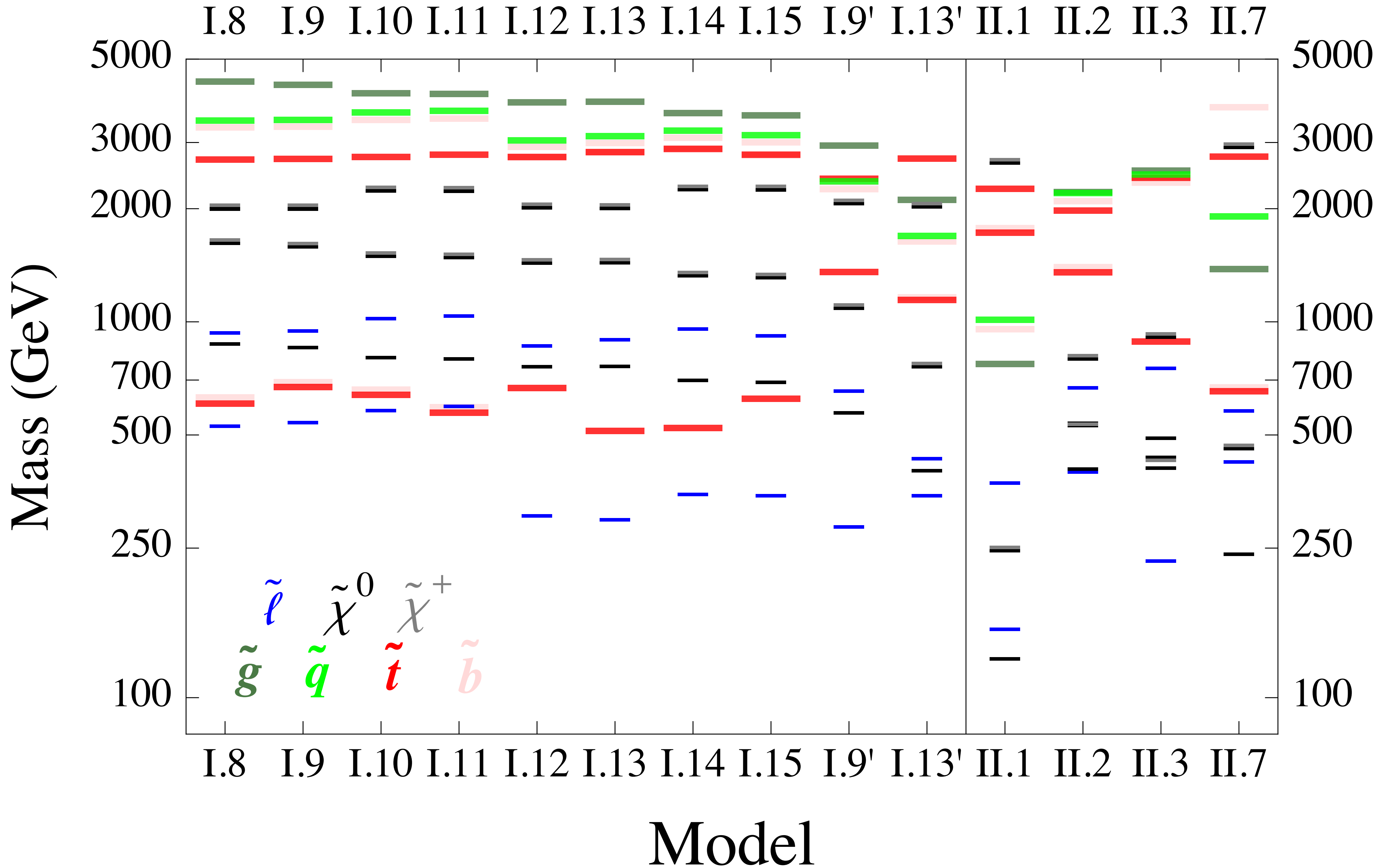


I.8 I.9 I.10 I.11 I.12 I.13 I.14 I.15 I.9' I.13' II.1 II.2 II.3 II.7
5000
3000
2000
1000
700
500
250
100
Mass (GeV)
Model



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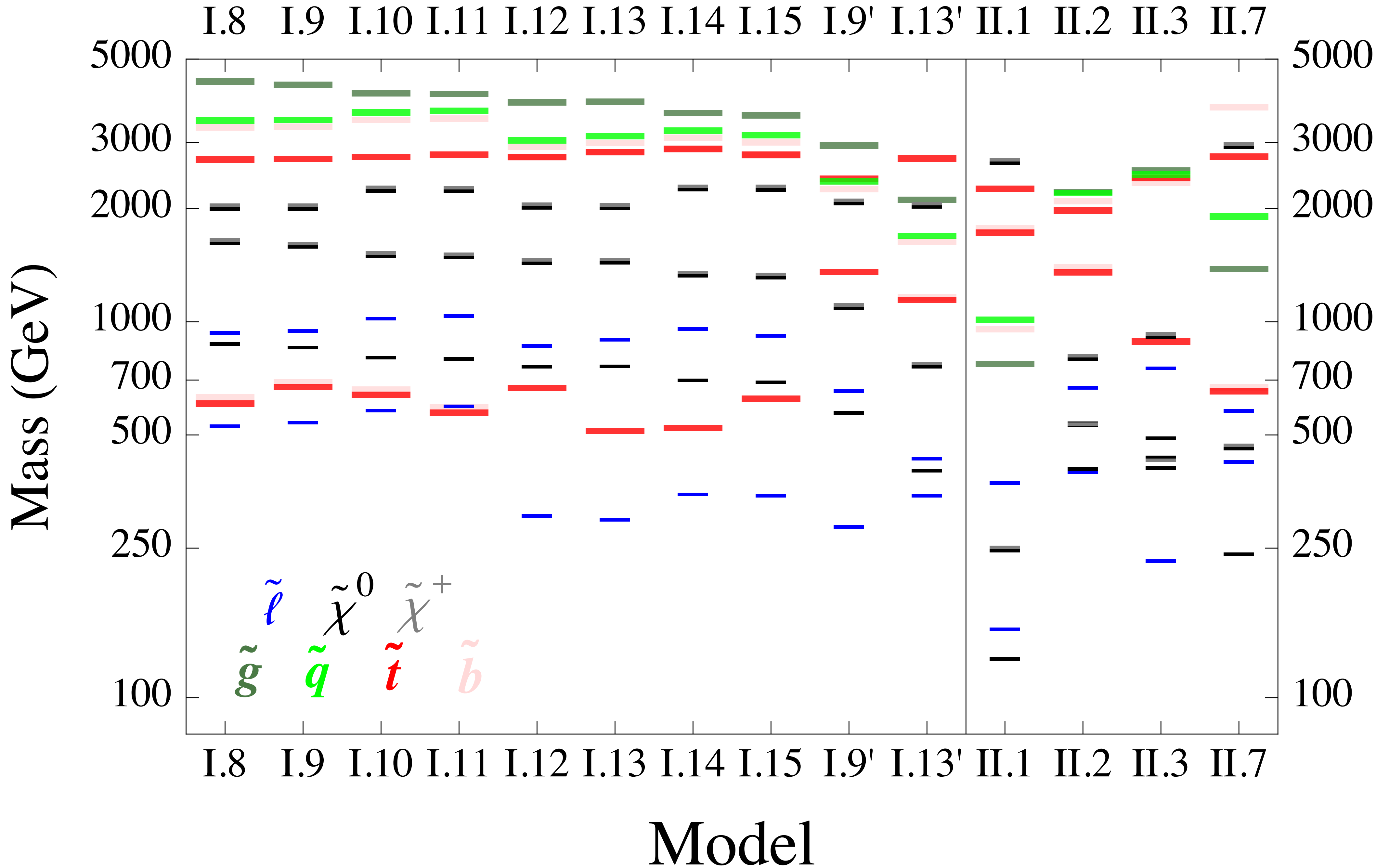

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Is the fact that we haven't seen superpartners yet an inevitable consequence of mh=125 GeV?

Strongly-coupled hidden sectors

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- Revisit the idea of hidden-sector sequestering.
- Proposed before as a way to solve the μ/Bμ problem (Dine et al ’04; Murayama et al ’07; Roy & Schmaltz ’07).

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- Proposed before as a way to solve the μ/Bμ problem (Dine et al '04; Murayama et al '07; Roy & Schmaltz '07).
- Their idea: Bμ comes from a non-chiral operator in the hidden sector. That operator could acquire an anomalous dimension through hidden-sector interactions

$$c_{B_\mu} \int d^4\theta \, \frac{X^\dagger X}{M^2} H_u H_d \quad \rightarrow \quad c_{B_\mu} \int d^4\theta \, \frac{\mathcal{O}_\Delta}{M^\Delta} H_u H_d$$

- If this anomalous dimension is large enough, it could suppress Bμ relative to μ.

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- If $\Delta > \Delta_X$, then $B\mu$ can be suppressed relative to μ^2:

$$c_\mu \int d^4\theta \, \frac{X^\dagger}{M^{\Delta_X}} H_u H_d \qquad \text{vs.} \qquad c_{B_\mu} \int d^4\theta \, \frac{\mathcal{O}_\Delta}{M^\Delta} H_u H_d$$

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- Our proposal: the same mechanism could also solve the A/m^2 problem! (Craig, Knapen & DS 1302.2642)

$$c_{A_{H_u}} \int d^4\theta \, \frac{X^\dagger}{M^{\Delta_X}} H_u^\dagger H_u \qquad \text{vs.} \qquad c_{m^2_{H_u}} \int d^4\theta \, \frac{\mathcal{O}_\Delta}{M^\Delta} H_u^\dagger H_u$$

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$$\beta_{c_{m^2_{H_u}}} = \Delta c_{m^2_{H_u}} + \mathcal{C}\, c^2_{A_{H_u}} + \ldots$$

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$$\beta_{c_{m^2_{H_u}}} = \Delta c_{m^2_{H_u}} + \mathcal{C}\, c^2_{A_{H_u}} + \ldots$$

  - Does integrating out the auxiliary fields reintroduce m^2 as in the little A/m^2 problem, spoiling the sequestering?

$$F^\dagger_{H_u} F_{H_u} + A_{H_u} F^\dagger_{H_u} H_u \quad \to \quad \delta m^2_{H_u} = +A^2_{H_u}$$

Subtleties and confusions

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- Perez, Roy & Schmaltz '08 argued that none of this happens. Their argument was based on field redefinitions:
  - If X is nearly free in the UV, then the A-term operator is redundant; it can be removed by the field redefinition

$$H_u \to H_u \left(1 + c_{A_{H_u}} \frac{X}{M}\right)$$

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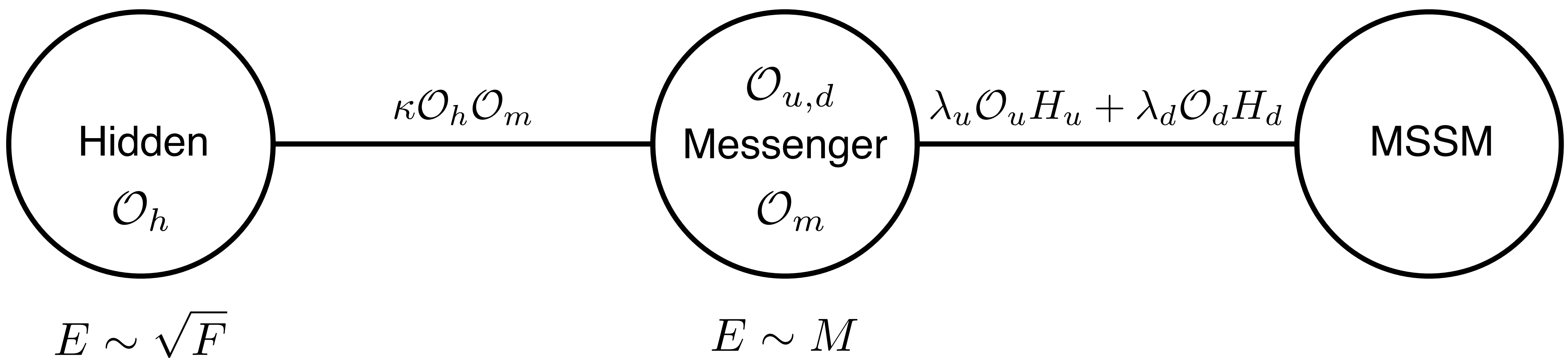
  - Then the field-redefined theory only has an m^2 operator, which can be fully sequestered!
- Craig and Green '09 pointed out several gaps in this argument:
  - If X is strongly coupled in the UV, field redefinitions are no longer valid.
  - The RG definitely contains a term proportional to $c_A{}^2$. Integrating the RG appears to produce an unsequestered term.

A fresh look at sequestering

- What is the correct picture?
- Using the correlator formalism of GGM, we brought a new angle to bear on these questions (Craig, Knapen & DS)



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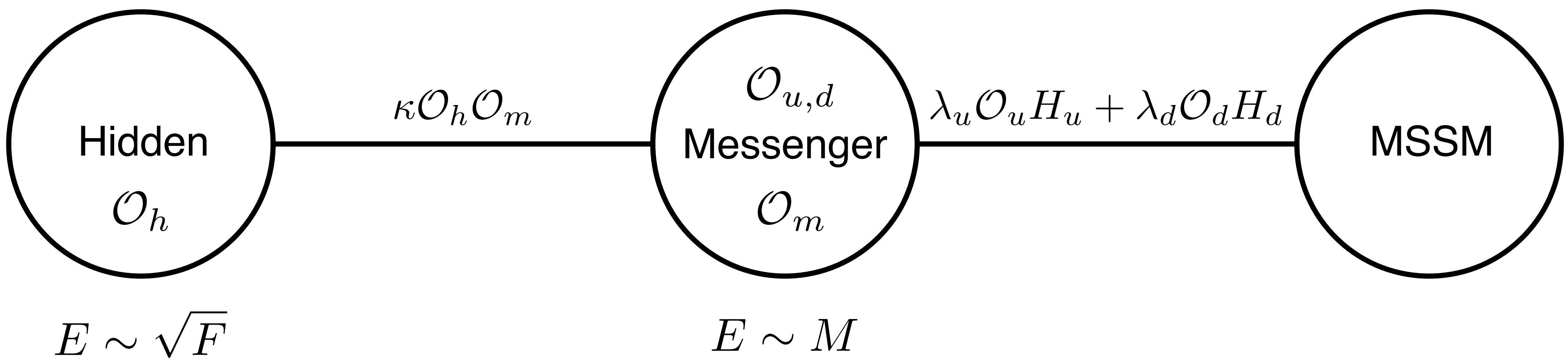

"General Messenger Higgs Mediation"

General Higgs Mediation

- The correlator formalism of GGM was first applied to Higgs-messenger interactions by Komargodski & Seiberg '08.
- Formulas for μ, Bμ, A and $m_{H_{u,d}}^2$ to leading order in $\lambda_{u,d}$, assuming a unified hidden+messenger sector:

$$\mu = -\lambda_u \lambda_d \int d^4x \left\langle Q^\alpha O_u(x) Q_\alpha O_d(0) \right\rangle_{h+m}$$

$$A_{u,d} = |\lambda_{u,d}|^2 \int d^4x \left\langle \bar{Q}^2 \left[O_{u,d}(x) O_{u,d}^\dagger(0) \right] \right\rangle_{h+m}$$

$$\hat{B}_\mu = -\lambda_u \lambda_d \int d^4x \left\langle Q^2 O_u(x) Q^2 O_d(0) \right\rangle_{h+m}$$

$$\hat{m}^2_{H_{u,d}} = -|\lambda_{u,d}|^2 \int d^4x \left\langle Q^2 \bar{Q}^2 \left[O_{u,d}(x) O_{u,d}^\dagger(0) \right] \right\rangle_{h+m}$$

GMHM expansion

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- We extended the KS results in two ways:
  - Separated messenger and hidden sector so we can take $F \ll M^2$ (cf Dumitrescu, Komargodski, Seiberg & DS '10).
  - Went to NLO in $\lambda_{u,d}$ for $B\mu$ and $m_{H_{u,d}}^2$ to address the subtleties.

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- Then can factorize messenger and hidden-sector correlators and use SUSY to simplify the former.

$$\kappa \langle \mathcal{O}_h \mathcal{O}_m \ldots \rangle_{h+m} = \kappa \langle \mathcal{O}_h \ldots \rangle_h \times \langle \mathcal{O}_m \ldots \rangle_m$$

GMHM Results

- Final GMHM formulas

$$\mu = \lambda_u \lambda_d \kappa^* \, \langle \bar{Q}^2 \mathcal{O}_h^\dagger \rangle_h \int d^4y \left\langle \mathcal{O}_m^\dagger(y) \mathcal{X}_\mu \right\rangle_m$$

$$A_{u,d} = |\lambda_{u,d}|^2 \kappa^* \, \langle \bar{Q}^2 \mathcal{O}_h^\dagger \rangle_h \int d^4y \left\langle \mathcal{O}_m^\dagger(y) \mathcal{X}_{A_{u,d}} \right\rangle_m$$

$$B_\mu = \lambda_u \lambda_d |\kappa|^2 \int d^4y \, d^4y' \left\langle Q^4 \Big[\mathcal{O}_h^\dagger(y) \mathcal{O}_h(y') \Big] \right\rangle_{h,full} \left\langle \mathcal{O}_m(y) \mathcal{O}_m^\dagger(y') \mathcal{X}_{B_\mu} \right\rangle_{m,full}$$

$$m^2_{H_{u,d}} = -|\mu|^2 + |\lambda_{u,d}|^2 |\kappa|^2 \int d^4y \, d^4y' \left\langle Q^4 \Big[\mathcal{O}_h^\dagger(y) \mathcal{O}_h(y') \Big] \right\rangle_{h,full} \left\langle \mathcal{O}_m(y) \mathcal{O}_m^\dagger(y') \mathcal{X}_{m^2_{H_{u,d}}} \right\rangle_{m,full}$$

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$B\mu$ and $m_{H_{u,d}}^2$ depend on the same hidden-sector 2-pt function

GMHM Results

- Final GMHM formulas

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Answers organize themselves into full correlators (connected + disconnected)

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- The answer only depends on $\langle Q^4 \mathcal{O}_\Delta \rangle$. Full sequestering!

$$B\mu \propto (\sqrt{F})^{\Delta}, \quad \mu \propto (\sqrt{F})^{\Delta_X}$$

Application to hidden-sector sequestering

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- Surprisingly, the field redefinition argument works beyond where it should!
- There is no little A/m^2 problem -- the disconnected A^2 contribution to m_H^2 is absorbed into the full hidden-sector 2-pt function, which then becomes sequestered via the OPE.
- Why did the RGEs give a misleading result? $\beta_{c_\Delta} = \Delta c_\Delta - \mathcal{C}_\Delta c_A^2$

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$$m_{H_u}^2 = (\dots)\left(\frac{\sqrt{F}}{M}\right)^\Delta + \left(|\langle Q^2 \mathcal{O}_h\rangle|^2 - \sum_i \frac{\mathcal{C}_{\Delta_i}}{(\sqrt{F})^{\gamma_i}}\langle Q^4 \mathcal{O}_{\Delta_i}\rangle\right)\frac{1}{(\sqrt{F})^{2\Delta_h}}|c_A(\sqrt{F})|^2$$

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vanishes by continuity of the OPE!

Subtleties and confusions begone

- By these considerations, all approaches to the phenomenon of hidden sector sequestering are brought into agreement.
- GMHM provides a powerful unified framework for describing all models of direct messenger-Higgs couplings.
    - Hidden sector sequestering is just a special case.
    - As a fixed order calculation, the GMHM calculation provides more control over the final result than previous approaches, which were based on the RG.

Summary

- A 125 GeV Higgs in the MSSM calls for $m_{\tilde{t}} \gtrsim 1 \text{ TeV}$ and the "maximal mixing" scenario: $A_t \sim \sqrt{6} m_{\tilde{t}}$.
- In this talk, we have surveyed the different options for achieving large A-terms in the MSSM.
  - A-terms from RG
    - needs heavy gluinos and high messenger scale
  - A-terms from MSSM/messenger interactions
    - weakly coupled: messengers must be MGM-type
    - strong coupled: hidden sector sequestering is a viable option
- We have highlighted the difficulties for EWSB and naturalness posed by the A/m^2 problem and the little A/m^2 problem.

Some works in progress

- The correlator formulas of GMHM offer a way to parametrize sequestered models. We are currently studying the phenomenology of these models (Craig, Knapen & DS)

- Weakly-coupled models with squark-type MSSM/messenger interactions were less fine-tuned than the Higgs-type interactions. But these are not MFV in general. There could be nontrivial constraints from flavor and CP. We are currently studying this in detail (Evans, DS & Thalapallil)

The End