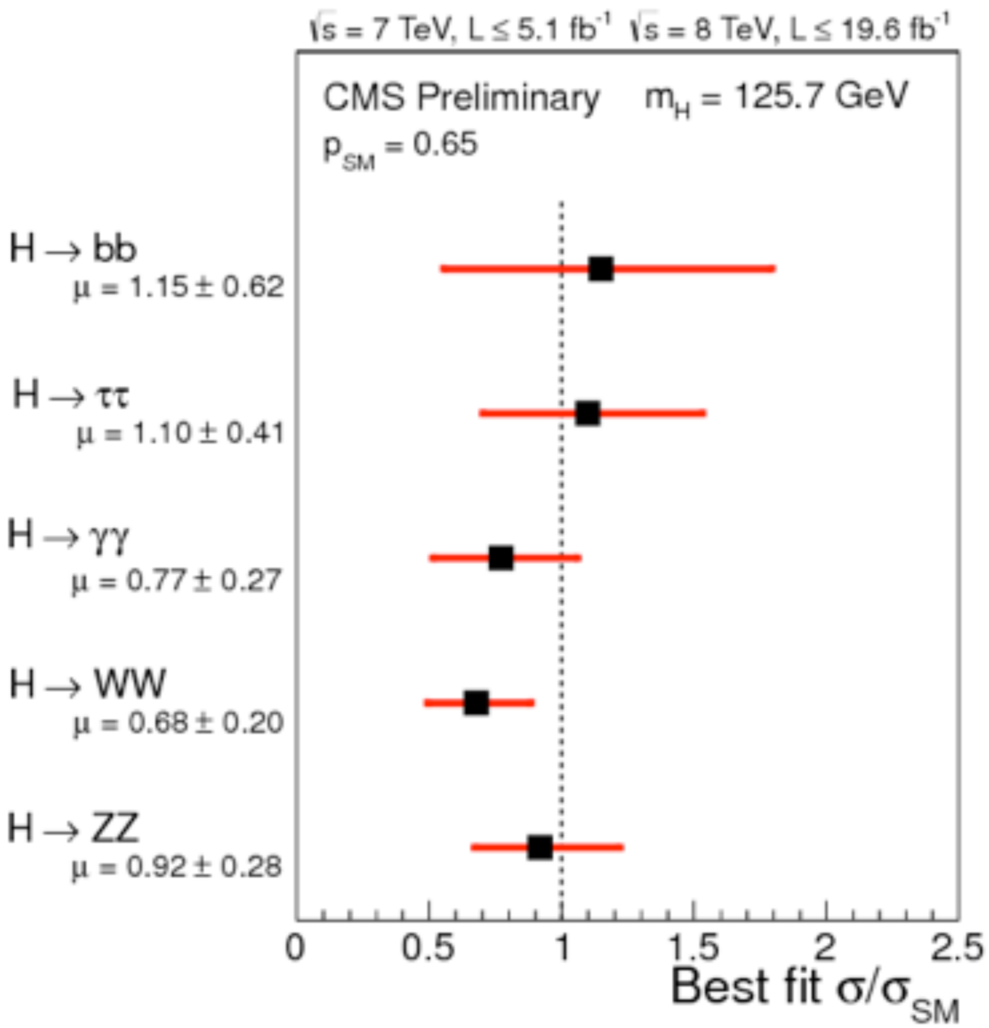
Overview of Models for A-terms and the Higgs

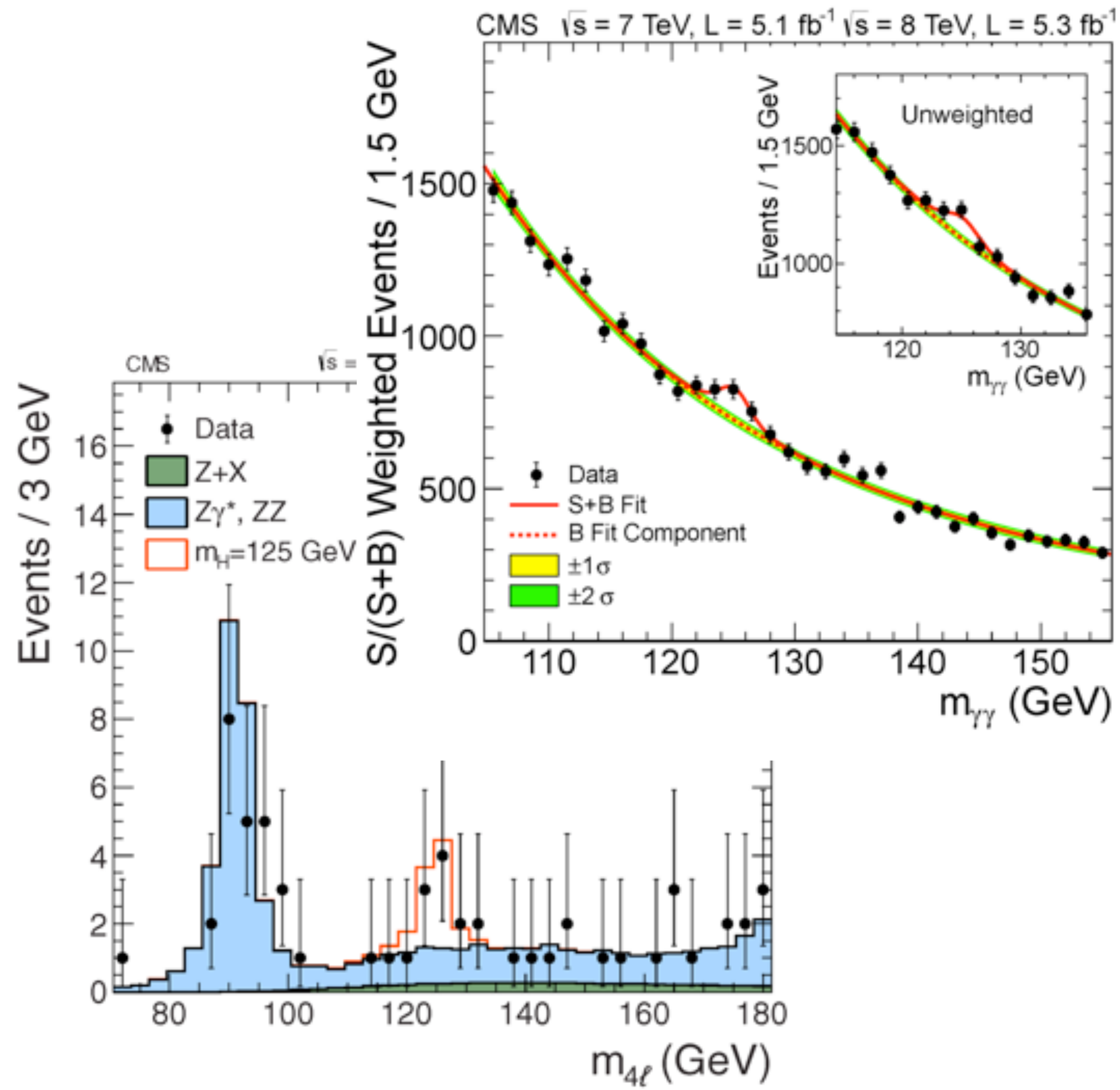
David Shih
NHETC, Rutgers

SUSY 2013, Trieste

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

In the past ~2 years we have learned a lot about the properties of the Higgs.





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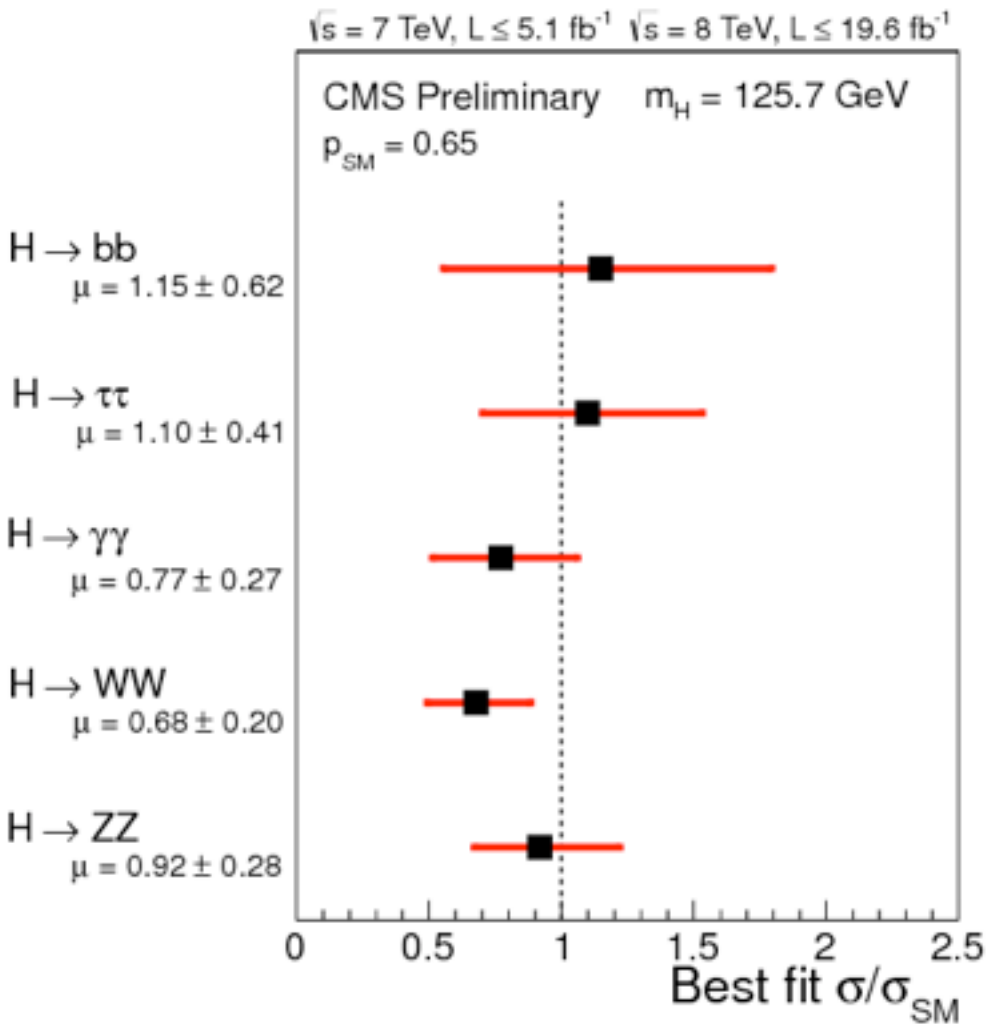

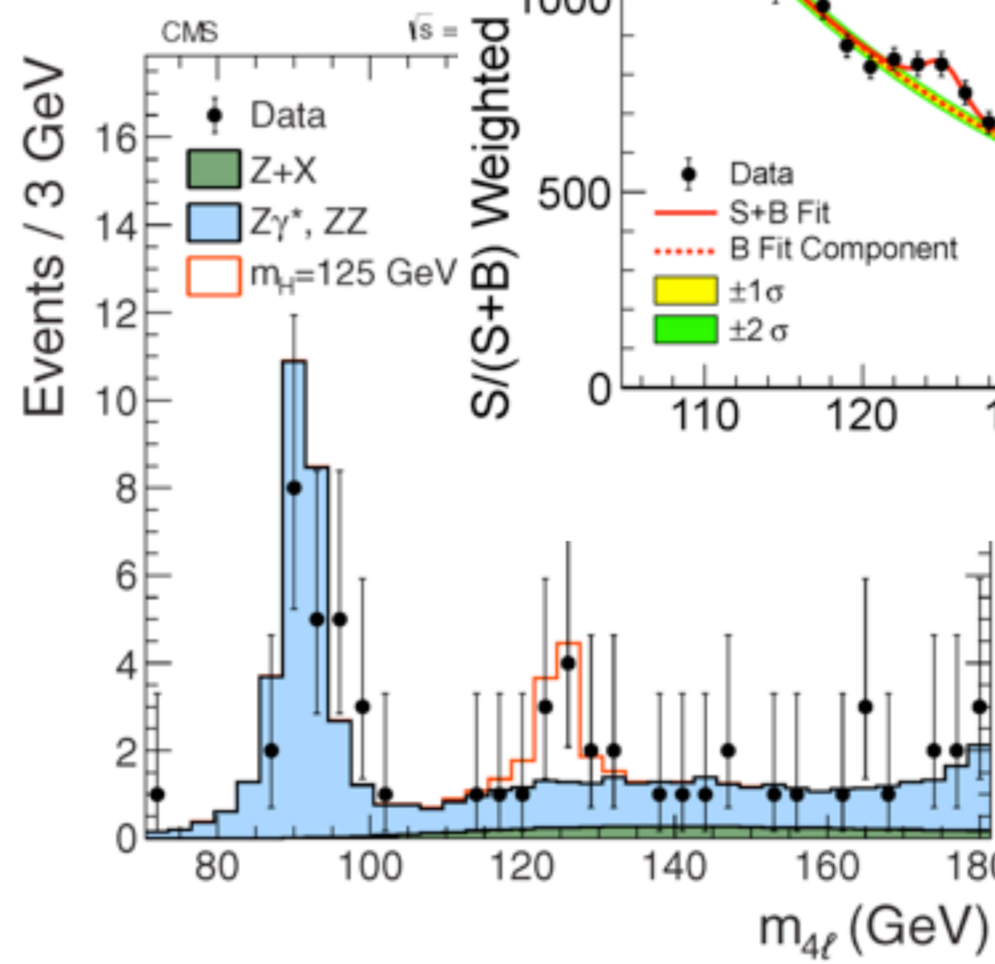

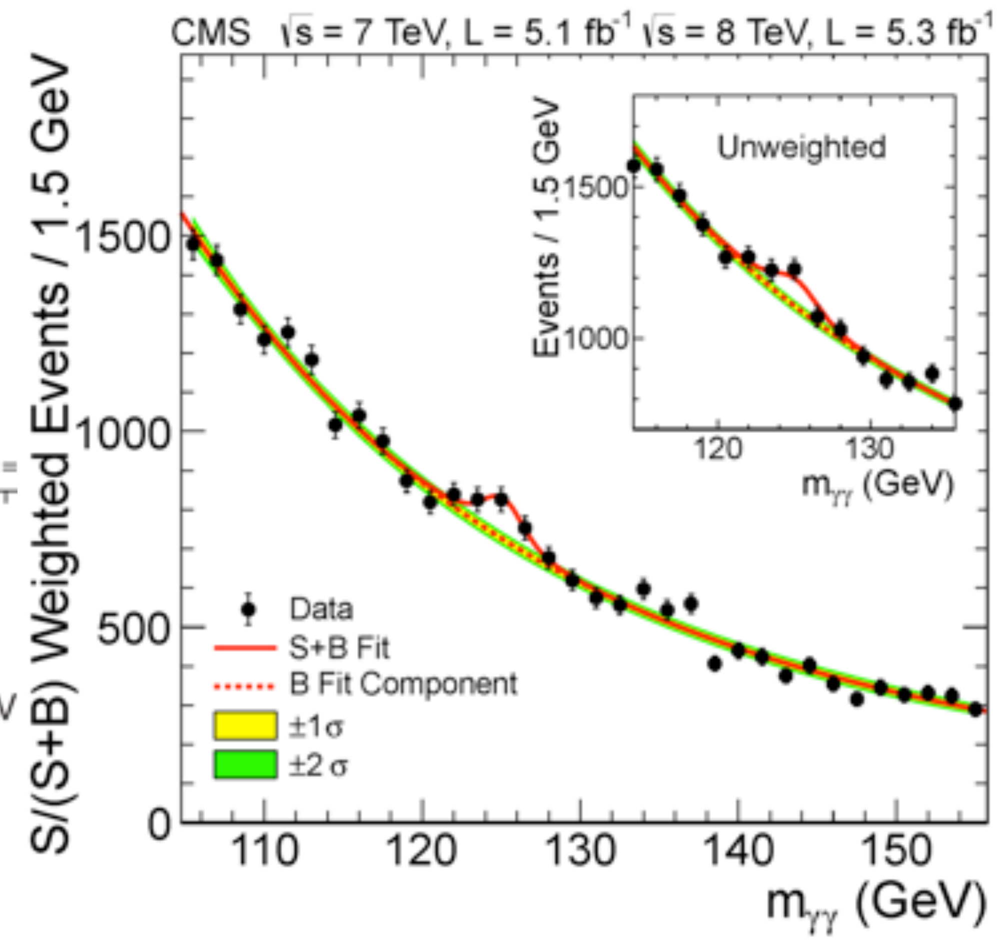

But there seem to be two very different points of view on these results...

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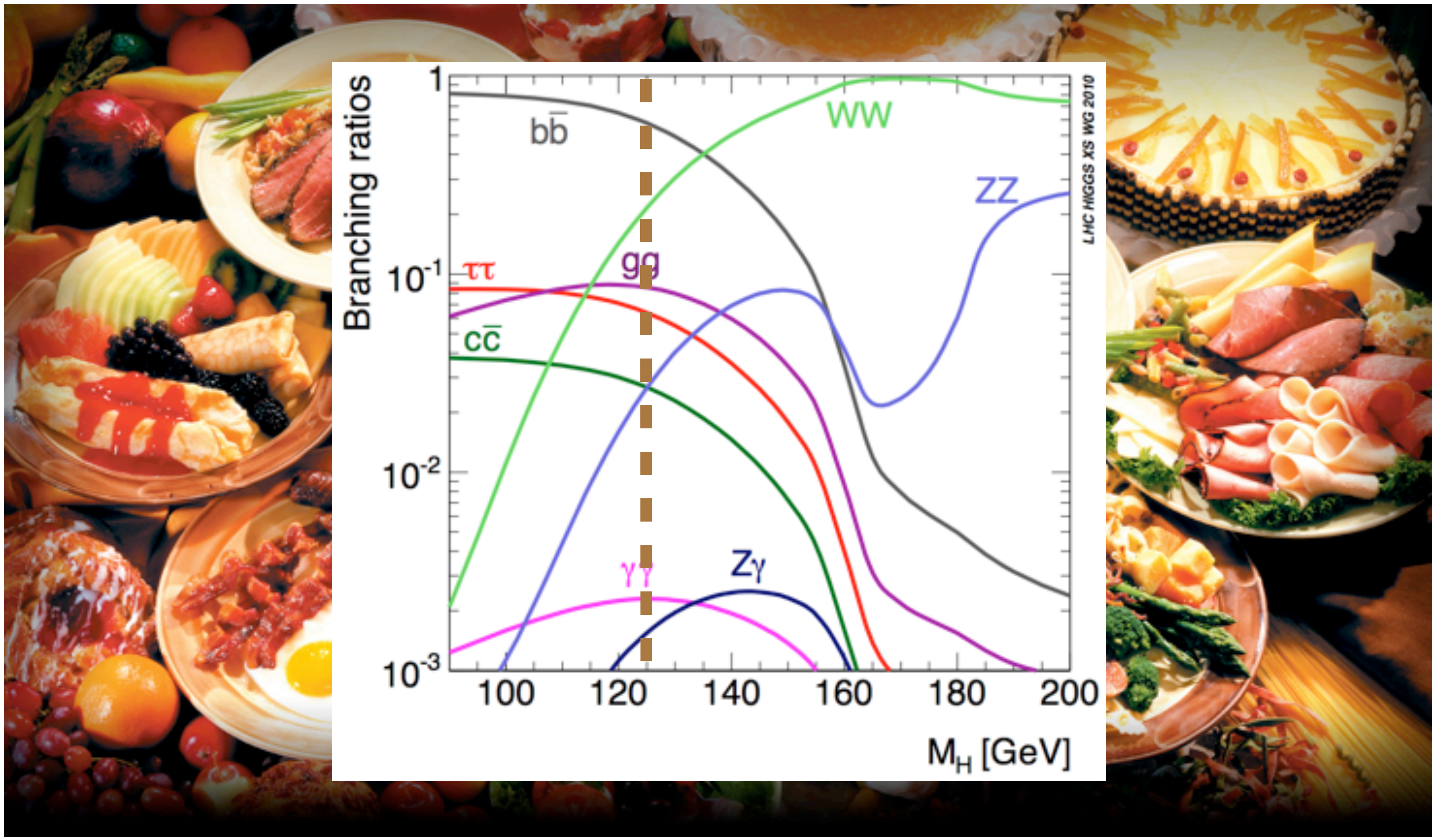

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So many of its decay modes are readily accessible at the LHC!

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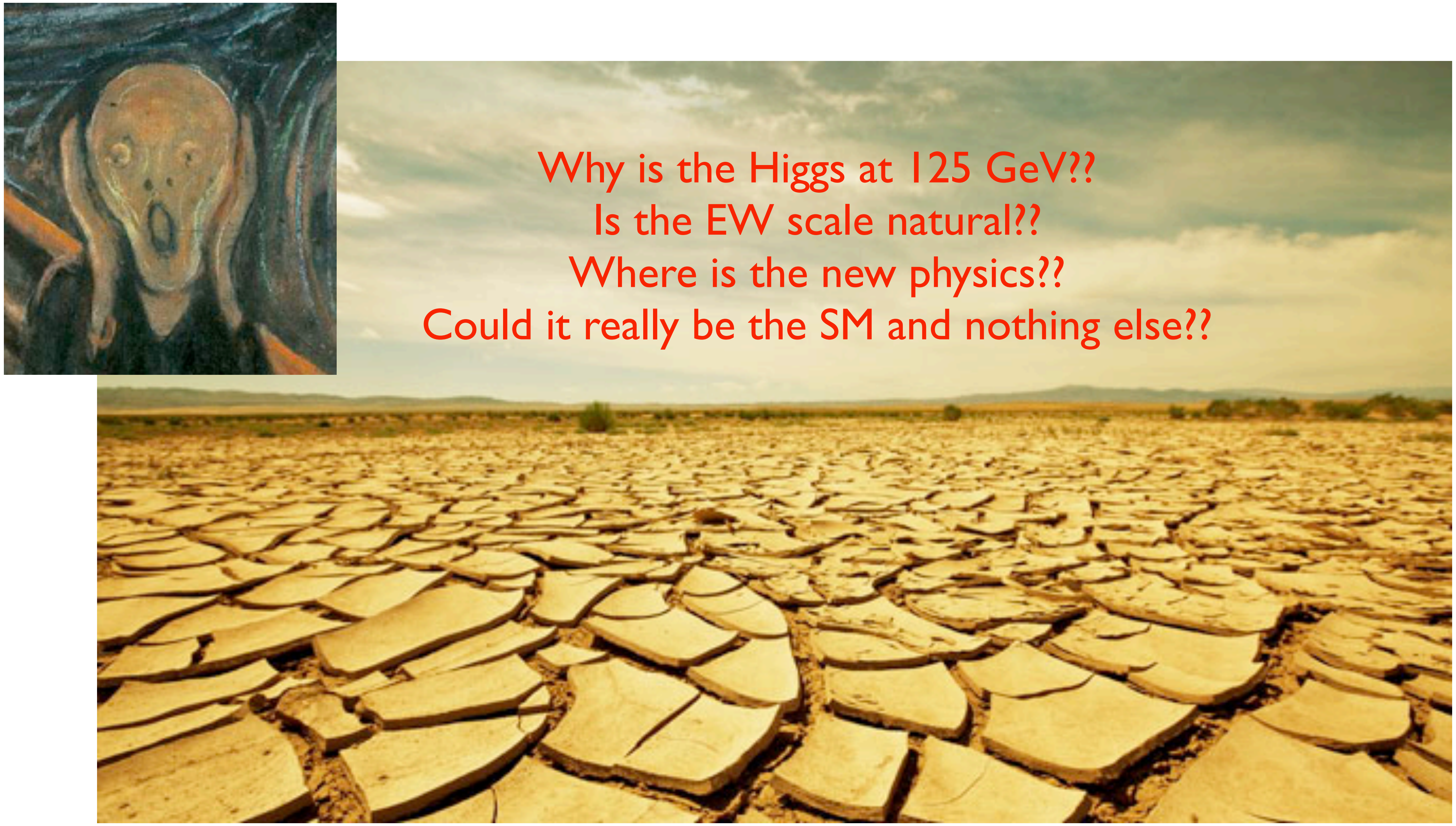

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  - extra vector-like generations
  - non-decoupling D-terms
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In many of these scenarios, given the Higgs at 125 GeV, we shouldn't have seen the superpartners yet!

Draper, Meade, Reece, DS
Craig, Knapen, DS, Zhao
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Evans & DS

Evans, Ibe, Shirai, Yanagida
Kang, Li, Liu, Tong, Yang
Abdullah, Galon, Shadmi, Shirman
Brummer, Kraml, Kulkarni
Byakti & Ray
Jelinski
....

Motivating m_h from A_t

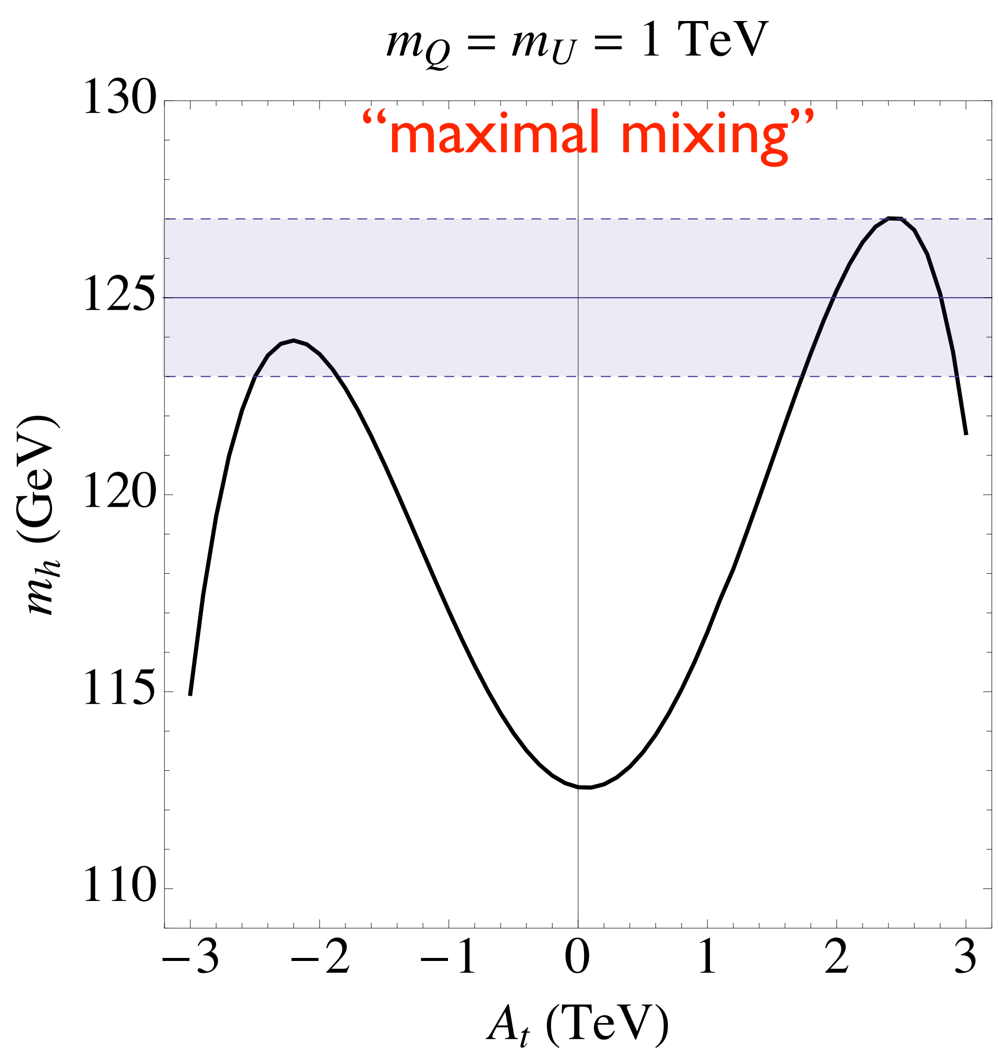
- My collaborators and I (and many others) have been working on obtaining the Higgs mass from large A-terms in the MSSM.
- Many motivations for this:
  - Least fine-tuned option with minimal SUSY
    - The alternative is very heavy stops ... orders of magnitude more tuning
  - Surprisingly unexplored territory
    - Before the Higgs discovery, there was not much systematic effort to build models for A-terms. An interesting frontier awaits!
  - Interesting challenges for model building
    - GMSB doesn't do it
    - Requirement of large A-terms is a strong constraint on models
    - Solving the constraints leads to specific models with detailed, testable predictions for the LHC

Higgs Mass Basics

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{A_t^2}{M_S^2}\left(1 - \frac{A_t^2}{12M_S^2}\right)\right) + \dots$$

M_S is the SUSY scale set by the stop masses.

$$M_S^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$$



The trilinear "A-term" A_t is responsible for mixing the two stops.

$$m_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 & A_t v_u \\ A_t^* v_u & m_{U_3}^2 \end{pmatrix}$$

$$-\mathcal{L}_{soft} \supset m_{Q_3}^2 |\tilde{Q}_3|^2 + m_{U_3}^2 |\tilde{U}_3|^2 + A_t H_u \tilde{Q}_3 \tilde{U}_3 + c.c.$$

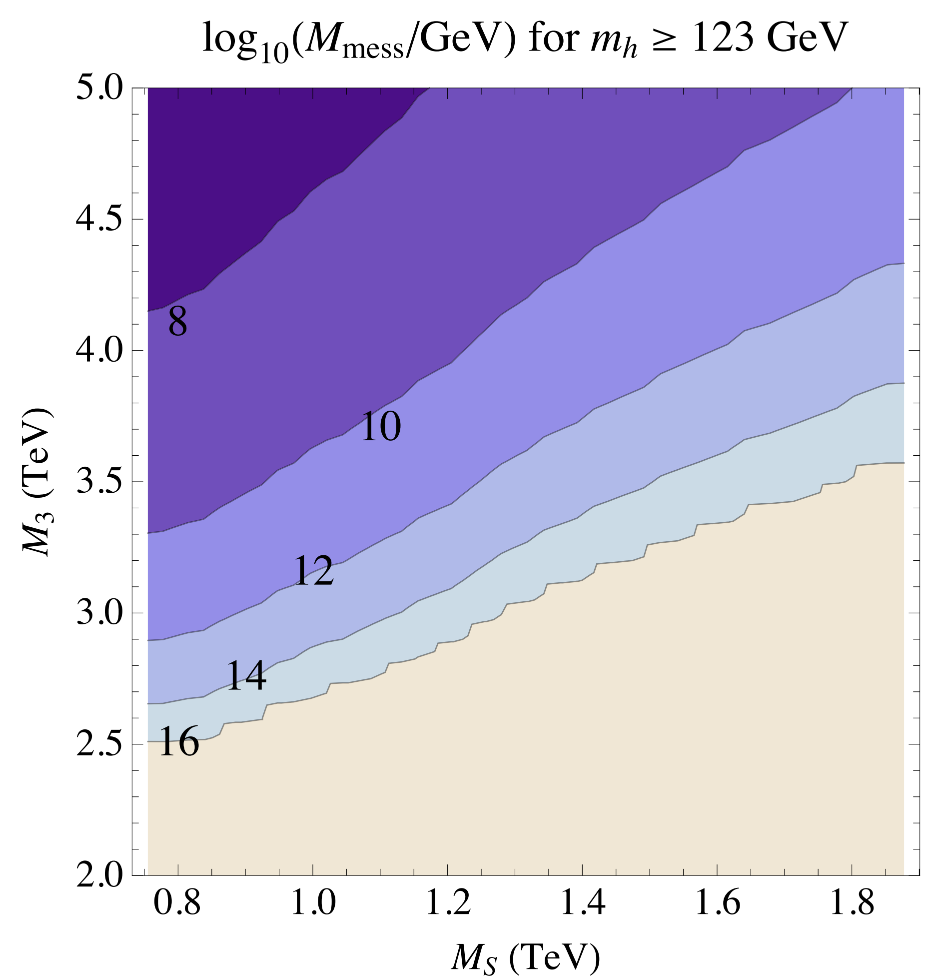
Overview of the strategies

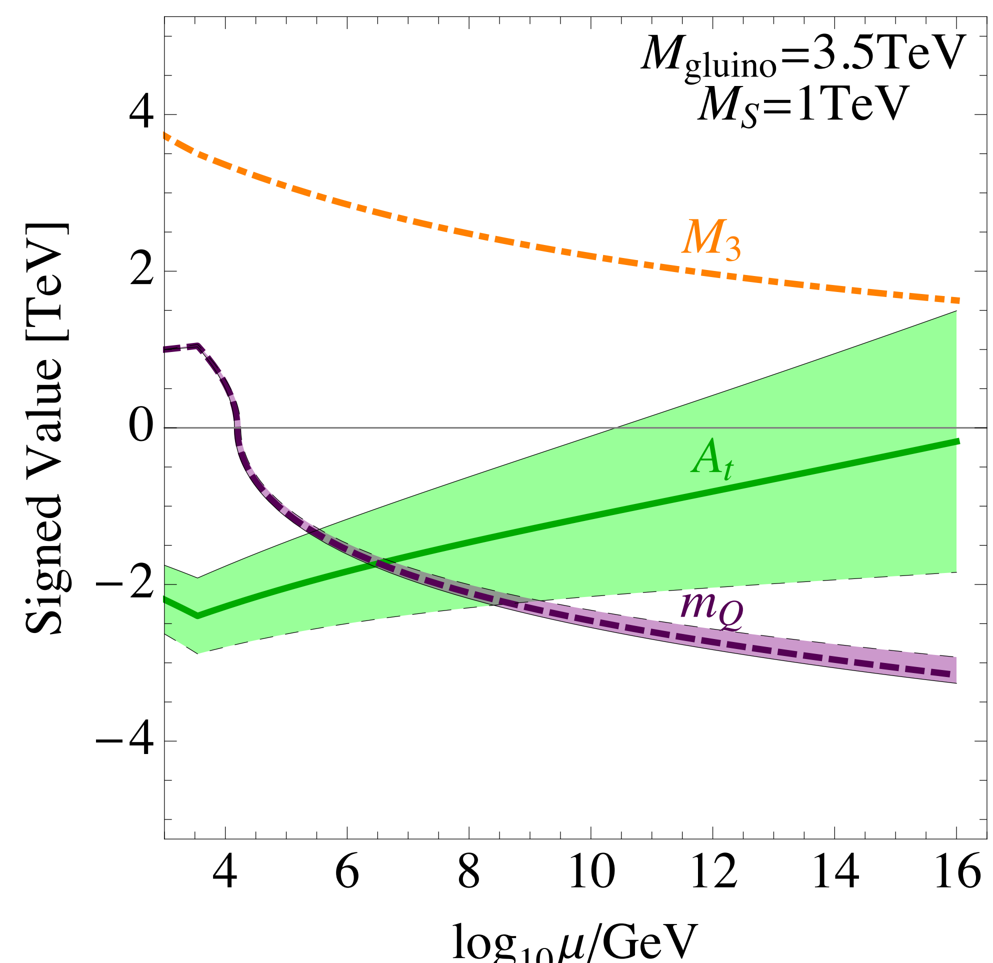
- Where can large A-terms come from?
  - A-terms at the Planck scale?
    - Does not solve the SUSY flavor problem...
  - A-terms from MSSM RGs
    - The only option for pure gauge mediation models
  - A-terms at the messenger scale
    - Requires direct messenger-MSSM interactions

A-terms through RG

$$16\pi^2 \frac{dA_t}{dt} \approx 12 y_t^2 A_t + \frac{32}{3} g_3^2 M_3$$

Large A-terms through the RG require $M_3 \gtrsim 2.5$ TeV and $M_{mess} \gtrsim 10^8$ GeV.

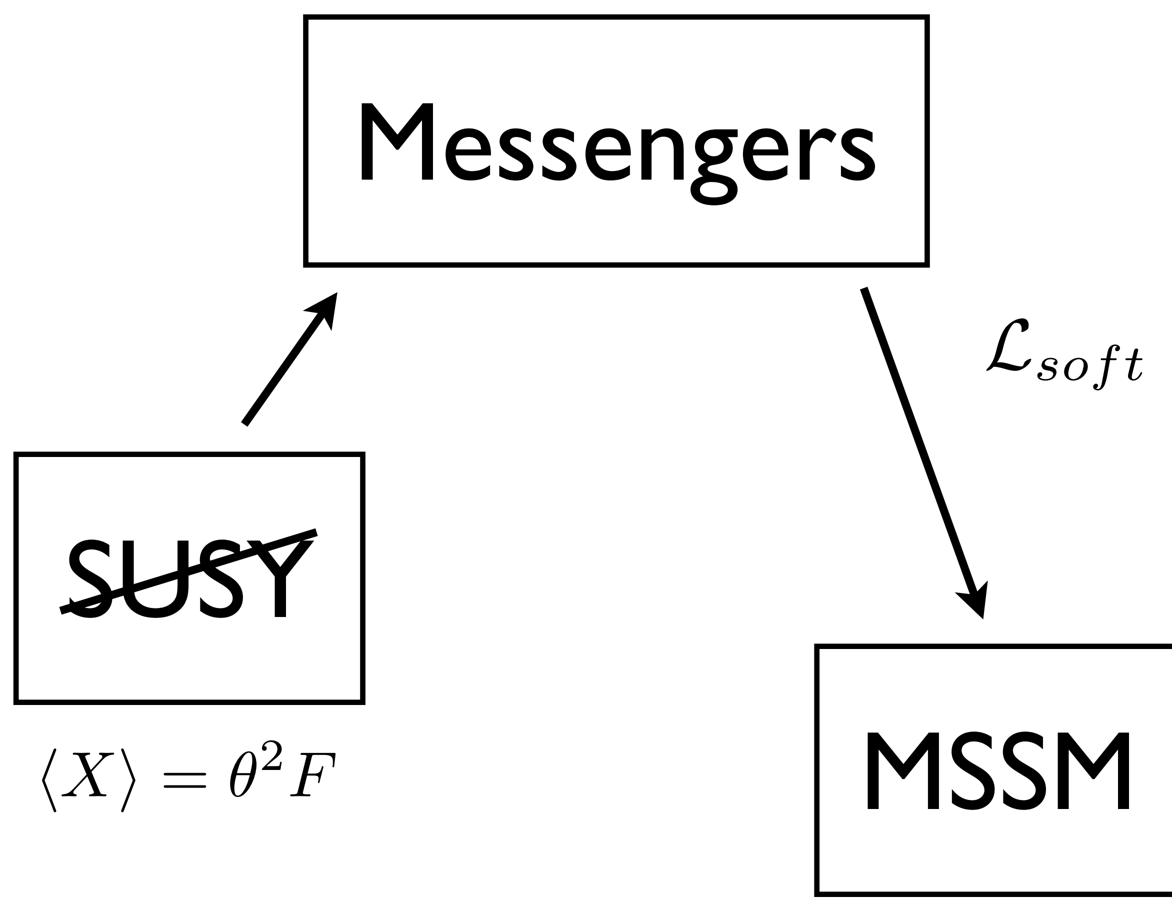




(Draper, Meade, Reece, DS)

A-terms through Messengers

- A-terms can also arise through integrating out the messengers of SUSY-breaking.



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

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

- Gauge interactions not enough! Need direct MSSM-messenger couplings.

Effective operators for A-terms

- A-terms originate from the effective Kahler potential operators:

$$\mathcal{L} \supset \int d^4\theta \, \frac{1}{M} \left(XQ^\dagger Q + XU^\dagger U + XH_u^\dagger H_u \right)$$

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Substitute SUSY-breaking spurion $\langle X \rangle = \theta^2 F$

Integrate over superspace $Q_i^\dagger \to F_{Q_i}^\dagger, \text{ etc}$

Use Yukawa couplings

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- Note:
  - The Higgs-type A-terms are automatically MFV (proportional to the Yukawas)
  - The squark-type A-terms are not automatically MFV

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

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

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- This is disastrous!

"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:

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- Suggests there should be a common solution?

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$$m_{ij} = 0 \ , \ \ \langle X \rangle = M + \theta^2 F \quad \Rightarrow \quad Z_Q^{(1-loop)} = c \ \log X^\dagger X$$

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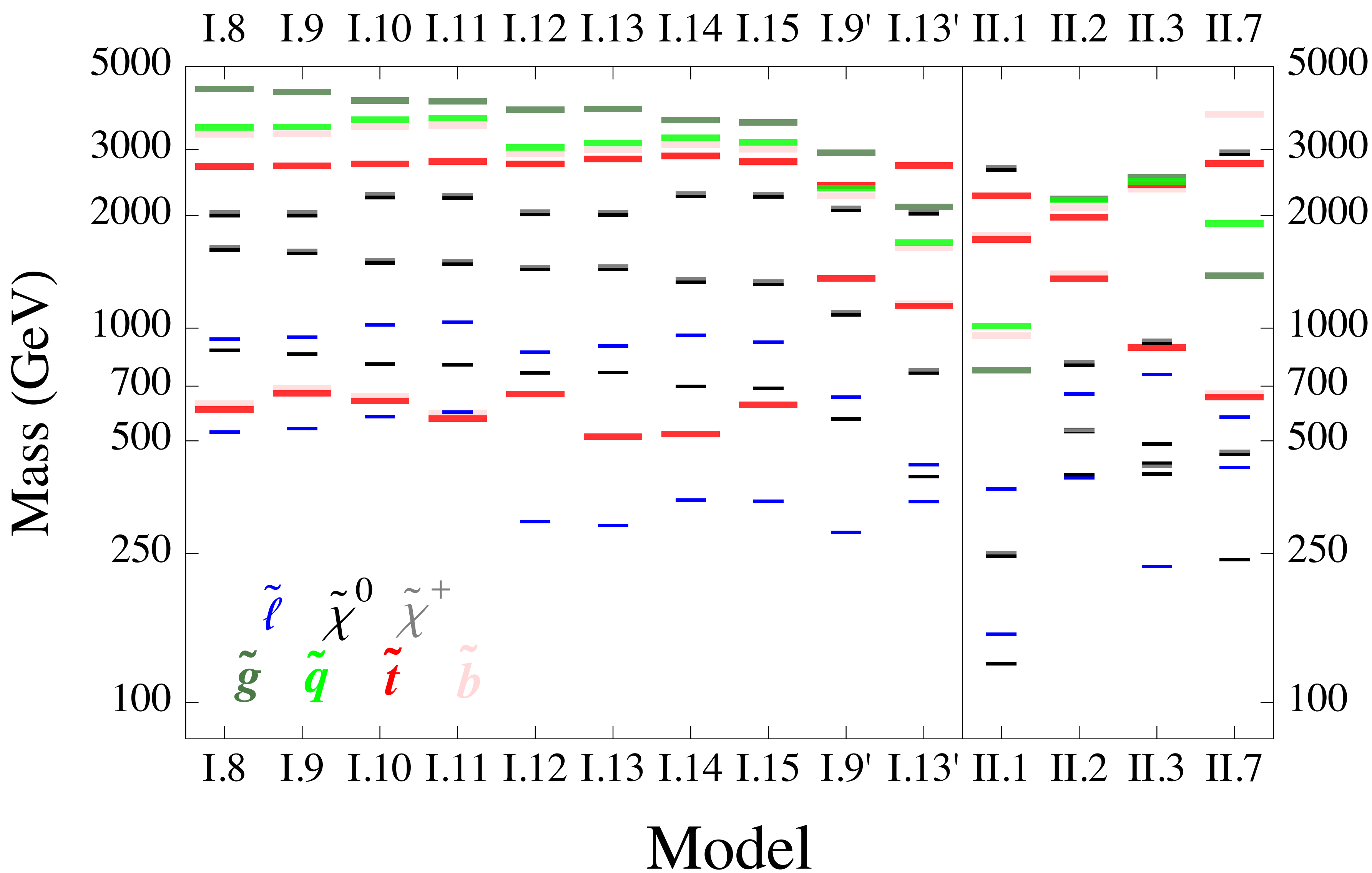
- The messengers must be those of Minimal Gauge Mediation! (Dine, Nelson, Shadmi & Shirman)

Evans & DS
see also
Byakti & Ray

We recently classified all MSSM-messenger couplings consistent with perturbative SU(5) unification. There are 31 couplings in all.

Turning on one coupling at a time, we surveyed the phenomenology of the models.



Work in progress: investigating the flavor and CP constraints on these models.... (Evans, Thalapallil & DS)

All but one of the best-tuned points with mh=125 GeV were out of reach at 7+8 TeV LHC, but could be accessible at 14 TeV LHC (taus+MET, multileptons, stop searches)

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

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(Hidden sector sequestering)

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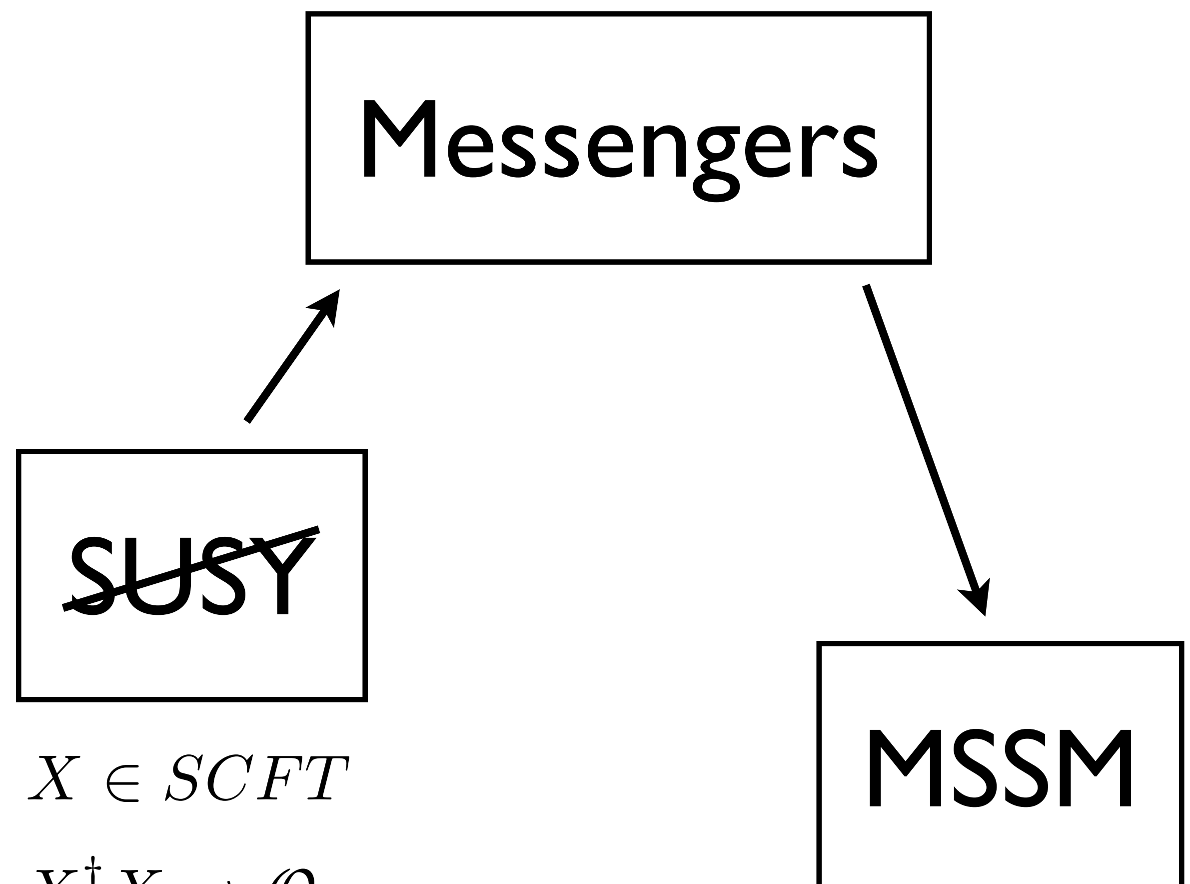

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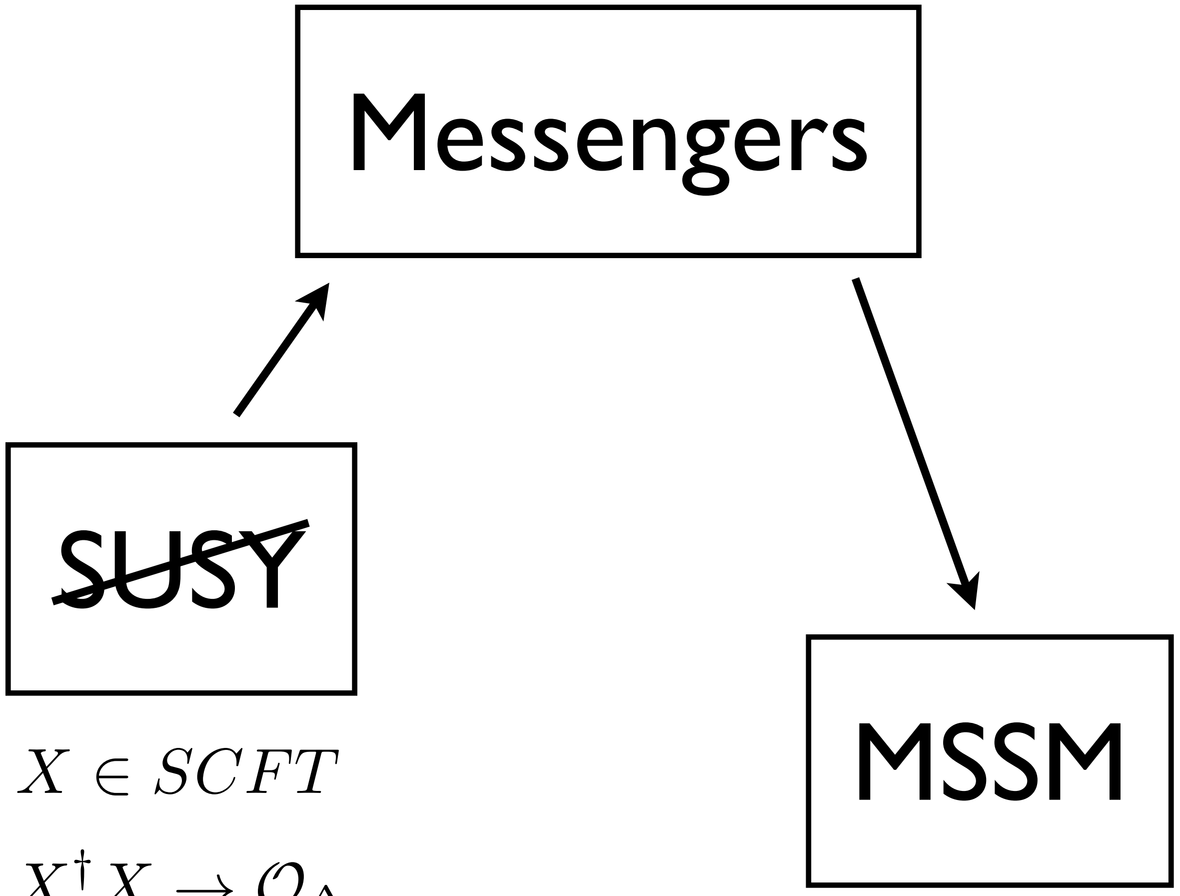

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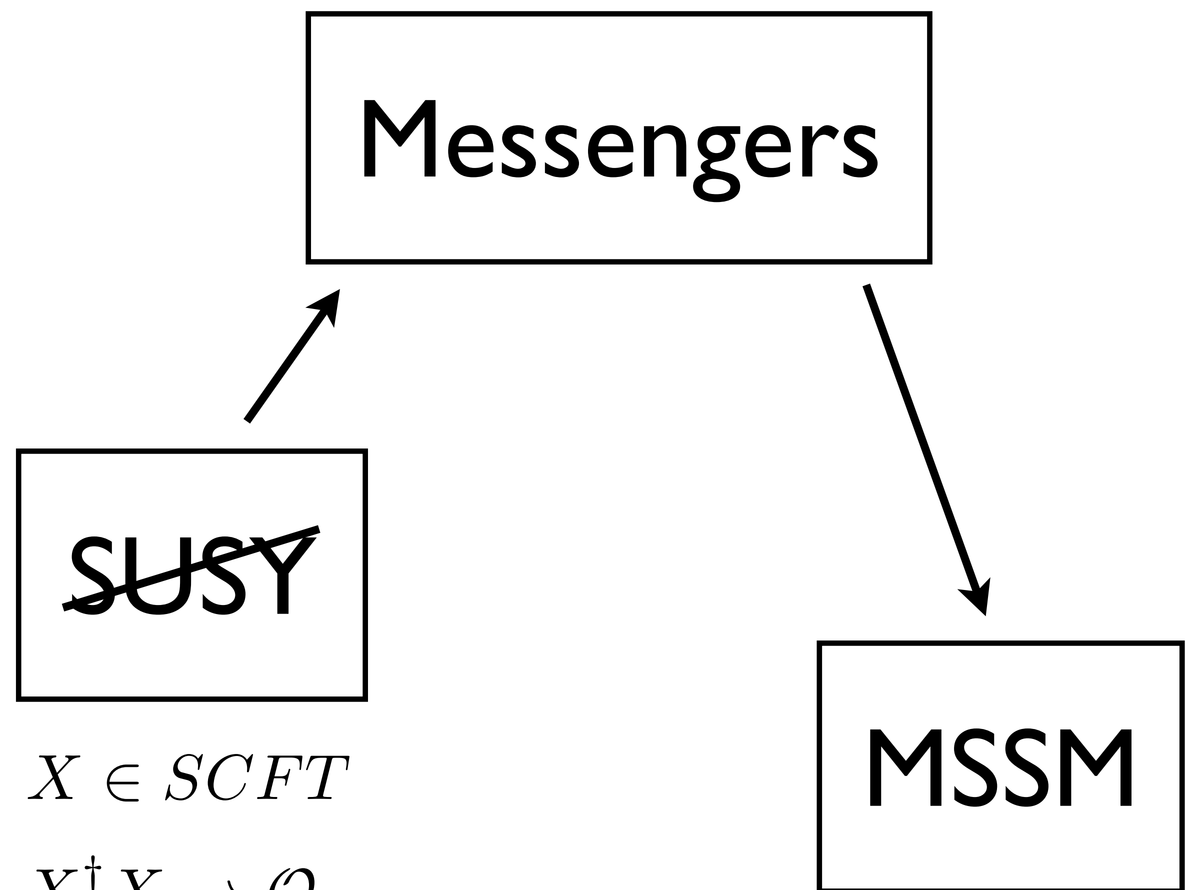

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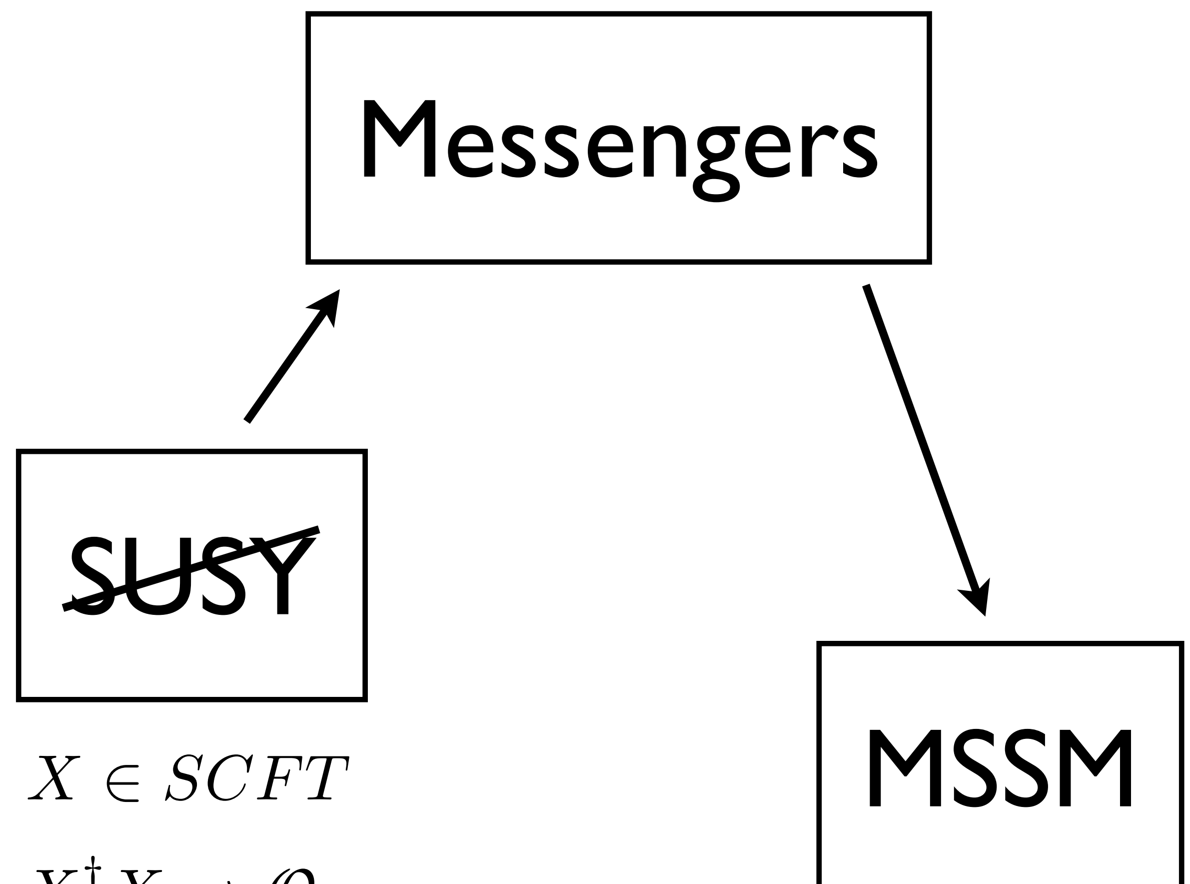

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  (Dine et al '04; Murayama, Nomura & Poland '07; Roy & Schmaltz '07)
- Our proposal: the same mechanism could simultaneously solve the A/m^2 problem!
  (Craig, Knapen & DS)

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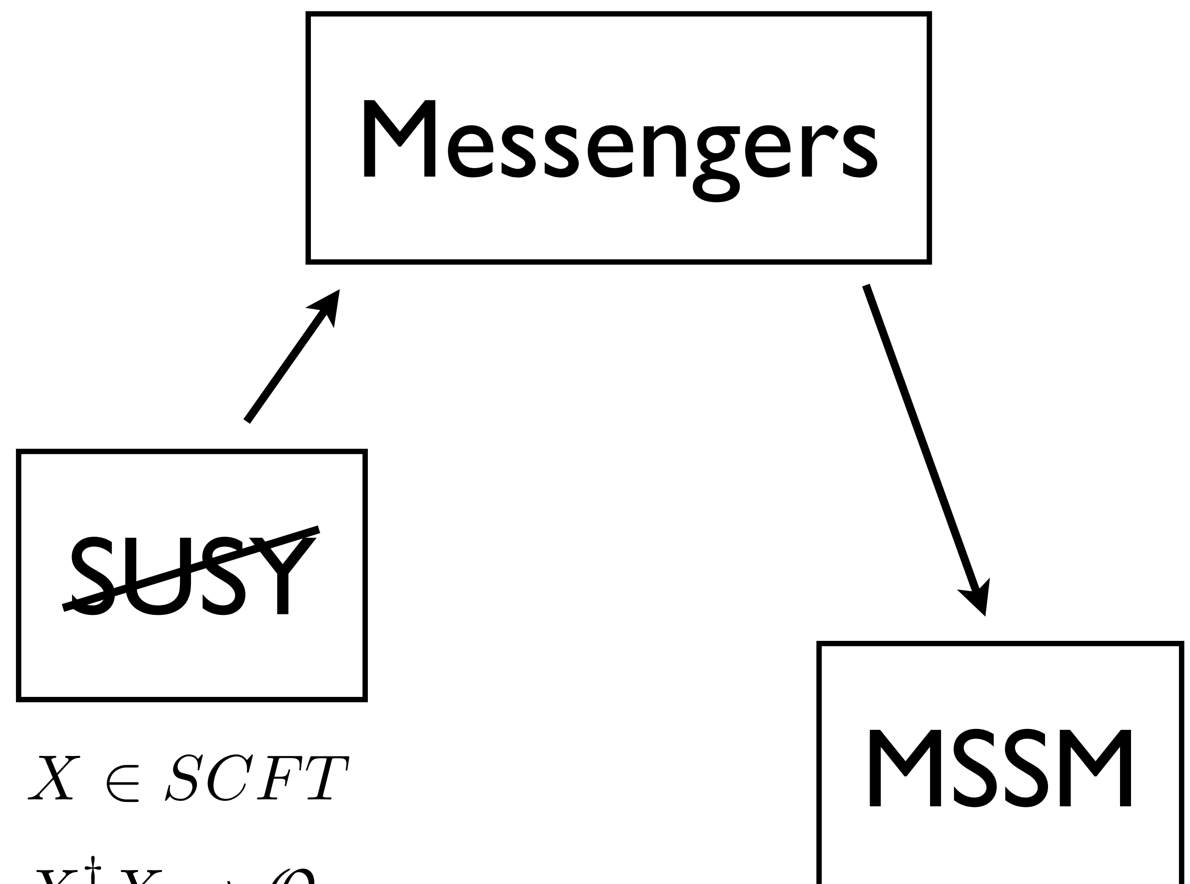

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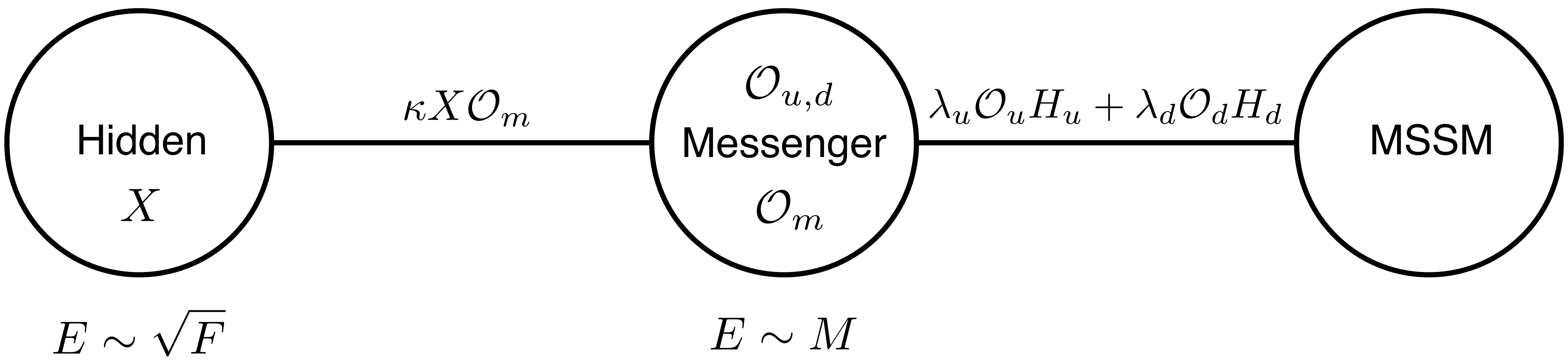
General Messenger Higgs Mediation

(Craig, Knapen & DS)



- We recently took a fresh look at hidden-sector sequestering using the correlator formalism of General Gauge Mediation.
  - Building off the previous work of Komargodski & Seiberg '08, we derived general formulas for soft parameters valid for any hidden and messenger sector. Sequestering follows as a special case.
- Previous approaches to sequestering were cast in terms of the RG. This is more like a fixed order calculation.
- It allows for more control over the final answer!

Final GMHM Formulas

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- Dimension 1 parameters:

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

$$\propto (\sqrt{F})^{\Delta_X + 1}$$

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- Dimension 2 parameters:

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$$\propto ??$$

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$$\propto ??$$

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Sequestering!!

Applications

- We are currently applying our result to study models where the sequestering is not total (Knapen & DS)
  - Total sequestering would be $B\mu = 0, \;\; m^2_{H_{u,d}} = -|\mu|^2$ .This boundary condition actually has a lot of trouble with achieving EWSB (Perez, Roy, Schmaltz; Asano, Hisano, Okada, Sugiyama)
  - Total sequestering requires long enough running with large enough anomalous dimension γ. However there are strong bounds on γ from the conformal bootstrap that limit this possibility. (Poland, Simmons-Duffins, Vichi)
  - This motivates us to study "partially sequestered" models where $B\mu$ and $m_{Hu,d}^2+|\mu|^2$ are not completely set to zero.
  - For this the GMHM formulas are absolutely essential!

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- Focusing on minimal SUSY, we surveyed the different ways to generate large A-terms from UV models.
  - A-terms from RG
    - need heavy gluinos and high messenger scale
  - A-terms from MSSM/messenger interactions
    - the A/m^2 problem
    - weakly coupled: messengers must be MGM-type
    - strongly coupled: hidden sector sequestering is a viable option.
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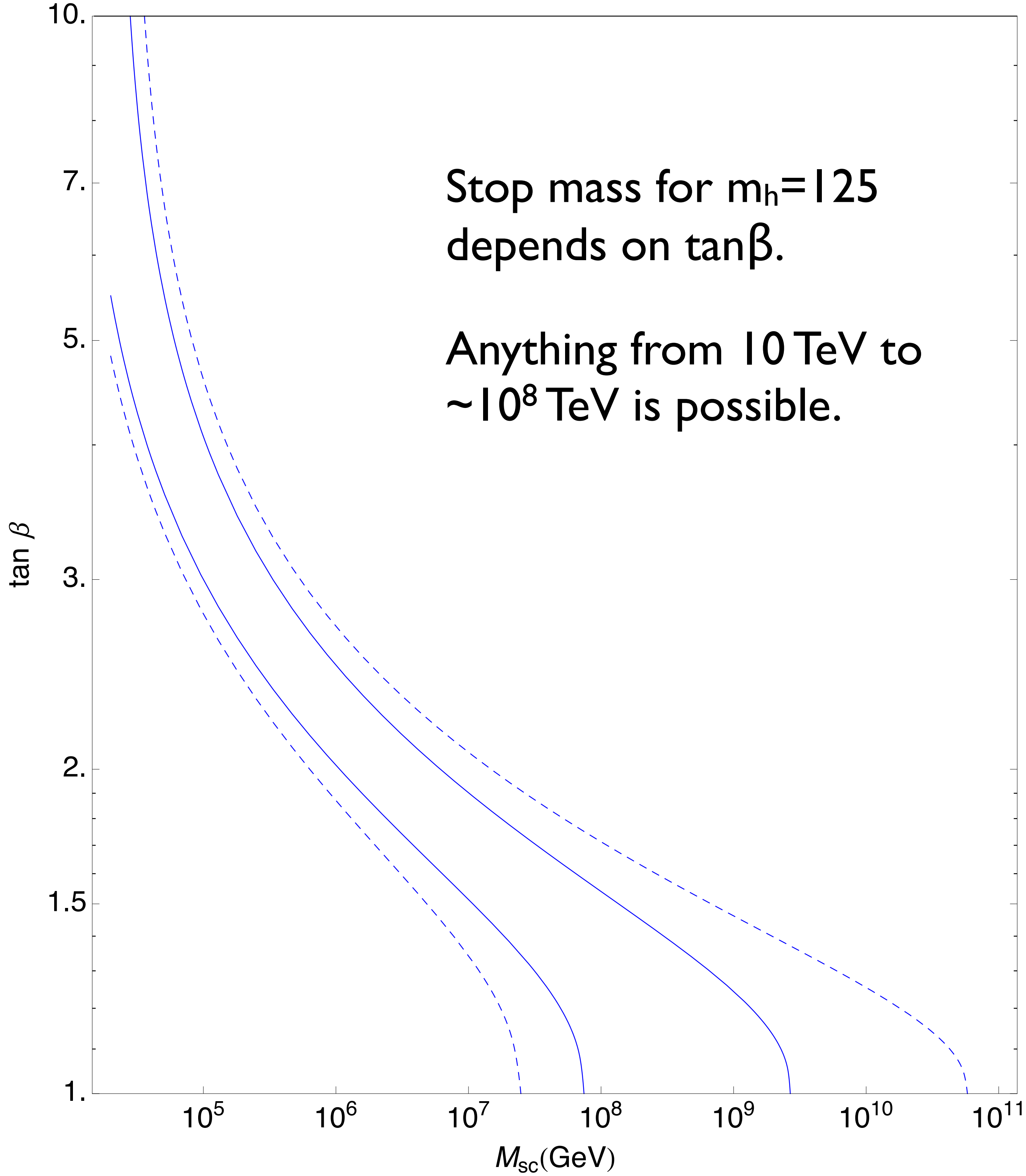
- Many are in reach of 14 TeV LHC. Exciting times are ahead?!

The End

Very Heavy Stops



- "Mini-split SUSY"
- Highly unnatural EW tuning but simplicity in "model space"
- 100-1000 TeV stops motivated by anomaly mediation, flavor problem, R-symmetry
- Can accommodate unification, dark matter.

Bhattacherjee, Feldstein, Ibe, Matsumoto, Yanagida

Arvanitaki, Craig, Dimopoulous, Villadoro

Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski

Beyond the MSSM

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- Two options:
  - "non-decoupling F-terms": new states couple to the Higgs via the superpotential
  - "non-decoupling D-terms": new states couple to the Higgs via the gauge potential

Non-decoupling F-terms

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- The NMSSM is a prime example of non-decoupling F-terms:

$$W = \lambda S H_u H_d \qquad \delta V_h \sim |\frac{\partial W}{\partial S}|^2 \sim \lambda^2 v^4 \sin^2 2\beta$$

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- Relaxing Landau pole constraint => motivated by Seiberg duality? aka "λ-SUSY", aka "Fat Higgs"

Barbieri, Hall, Nomura, Rychkov
Harnik, Kribs, Larson, Murayama
...
Hall, Pinner, Ruderman

Batra, Delgado, Kaplan & Tait '03

Non-decoupling D-terms

Batra, Delgado, Kaplan & Tait '03

Non-decoupling D-terms

- The basic idea: charge the Higgs under additional gauge group. When this gauge symmetry is broken non-supersymmetrically, an additional D-term potential for the Higgs is generated.

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- A simple $U(1)_x$ toy model: (H_u, H_d, Φ_+, Φ_-) charges (+1,-1,+1,-1)

$$W = S(\phi_+\phi_- - w^2) \qquad V_{soft} = m^2(|\phi_+|^2 + |\phi_-|^2)$$

$$\delta V_D = g_x^2(|H_u|^2 - |H_d|^2 + |\phi_+|^2 - |\phi_-|^2)^2$$

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$$\delta V_D = g_x^2(|H_u|^2 - |H_d|^2 + |\phi_+|^2 - |\phi_-|^2)^2$$

- In the presence of V_{soft}, the Higgs quartic gets a new term:

$$\delta V_h = g_x^2 \left(1 + \frac{2m_x^2}{m^2}\right)^{-1} (|H_u|^2 - |H_d|^2)^2$$

Non-decoupling D-terms

- Models with nonabelian groups (e.g. SU(2)) were also constructed
- Gauge coupling unification is nontrivial, but can be accommodated with enough complications (Batra, Delgado, Kaplan & Tait; Maloney, Pierce & Wacker; ...)
- Fine tuning ameliorated but not eliminated -- scales like $1/m_X^2$. For max 10% tuning consistent with EWPT and direct searches, must have m_X~3-10 TeV (Maloney, Pierce & Wacker)
- These models generically predict enhanced coupling to bb. Could be observable at LHC/ILC, but not necessarily. (Blum, D'Agnolo, Fan; Azatov, Chang, Craig, Galloway)

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#	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	$H_u\phi_{\bar{5},L}\phi_{1,S}$	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
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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	$H_u\phi_{\bar{5},L}\phi_{24,S}$	6	$\{0.225, 1.000\}$	0.54	13290	9785	3408	3850
I.6	$H_u\phi_{\bar{5},L}\phi_{24,W}$	6	$\{0.15, 1.025\}$	0.67	11835	8637	3259	3410
I.7	$H_u\phi_{\bar{5},D}\phi_{24,X}$	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	$Q\phi_{\bar{5},D}\phi_{\bar{5},L}$	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
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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
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
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
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
II.9	$UE\phi_{5,\overline{D}}$	1	$\{0.445, 1.46\}$	1.89	2004	1750	3373	2730
II.10	$H_uD\phi_{24,X}$	5	$\{0.42, 1.45\}$	2.13	2943	1649	282	3500
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
II.14	$H_uH_d\phi_{1,S}$	1^*	$\{0.125, 0.675\}$	0.55	7049	8051	3255	5000
II.15	$H_uH_d\phi_{24,S}$	5	$\{0.20, 1.00\}$	0.57	12047	9213	1628	4220
II.16	$H_uH_d\phi_{24,W}$	5	$\{0.2, 0.946\}$	0.64	11571	8789	3665	3460

We recently classified all MSSM-messenger couplings consistent with perturbative SU(5) unification (Evans & DS). There are 31 couplings in all.

Turning on one coupling at a time, we surveyed the phenomenology of the resulting models.

#	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	$H_u\phi_{\bar{5},L}\phi_{1,S}$	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	$H_u\phi_{\bar{5},L}\phi_{24,S}$	6	$\{0.225, 1.000\}$	0.54	13290	9785	3408	3850
I.6	$H_u\phi_{\bar{5},L}\phi_{24,W}$	6	$\{0.15, 1.025\}$	0.67	11835	8637	3259	3410
I.7	$H_u\phi_{\bar{5},D}\phi_{24,X}$	6	$\{0.3, 1.425\}$	2.04	3020	1743	576	3500
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I.9	$Q\phi_{\bar{5},D}\phi_{\bar{5},L}$	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
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II.7	$UD\phi_{\bar{5},D}$	1	$\{0.21, 1.26\}$	2.34	1374	1334	2998	2150
II.8	$QL\phi_{\bar{5},D}$	1	$\{0.14, 1.2\}$	1.51	1501	1204	2203	3700
II.9	$UE\phi_{5,\overline{D}}$	1	$\{0.445, 1.46\}$	1.89	2004	1750	3373	2730
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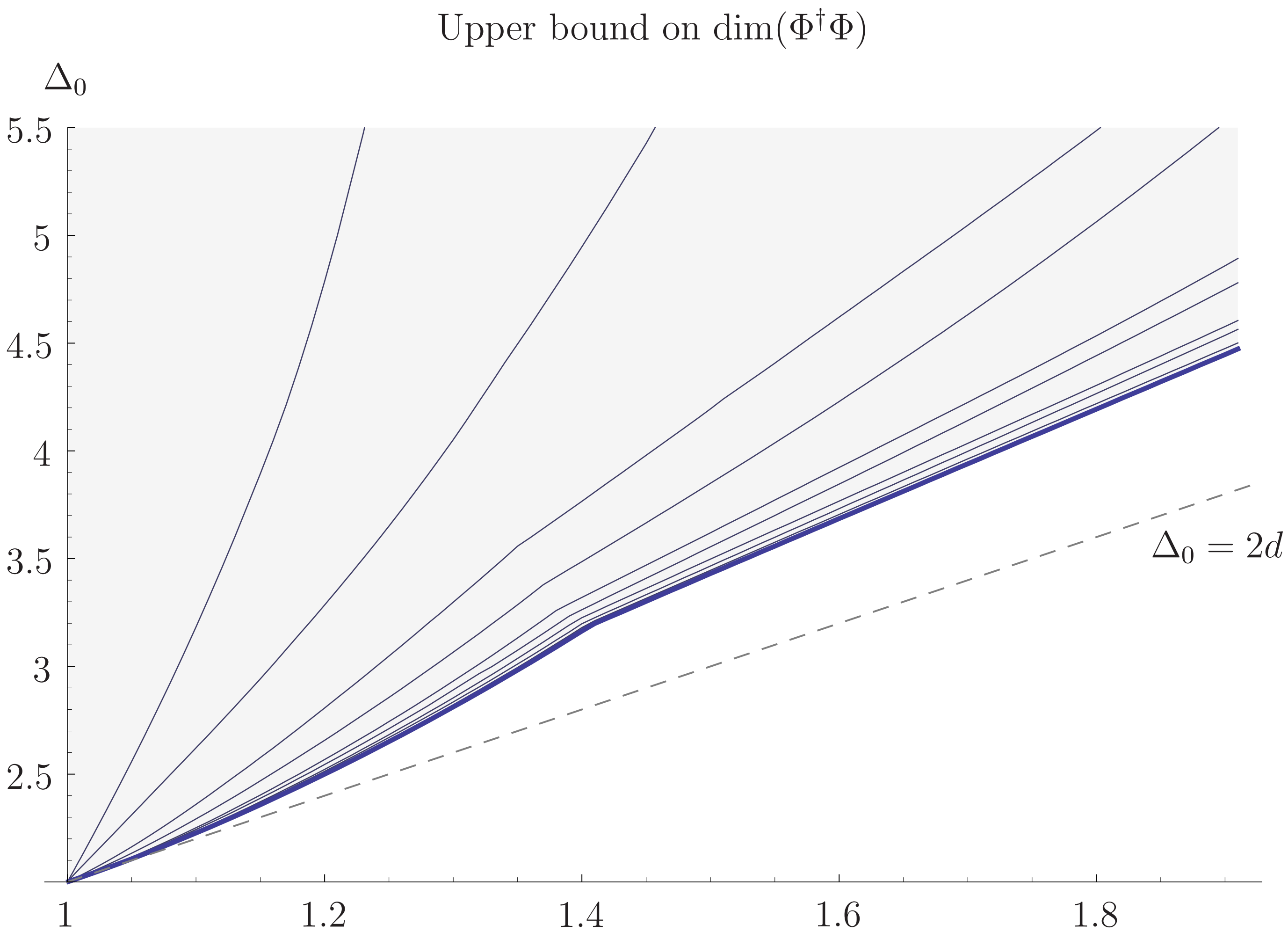
II.15	$H_uH_d\phi_{24,S}$	5	$\{0.20, 1.00\}$	0.57	12047	9213	1628	4220
II.16	$H_uH_d\phi_{24,W}$	5	$\{0.2, 0.946\}$	0.64	11571	8789	3665	3460

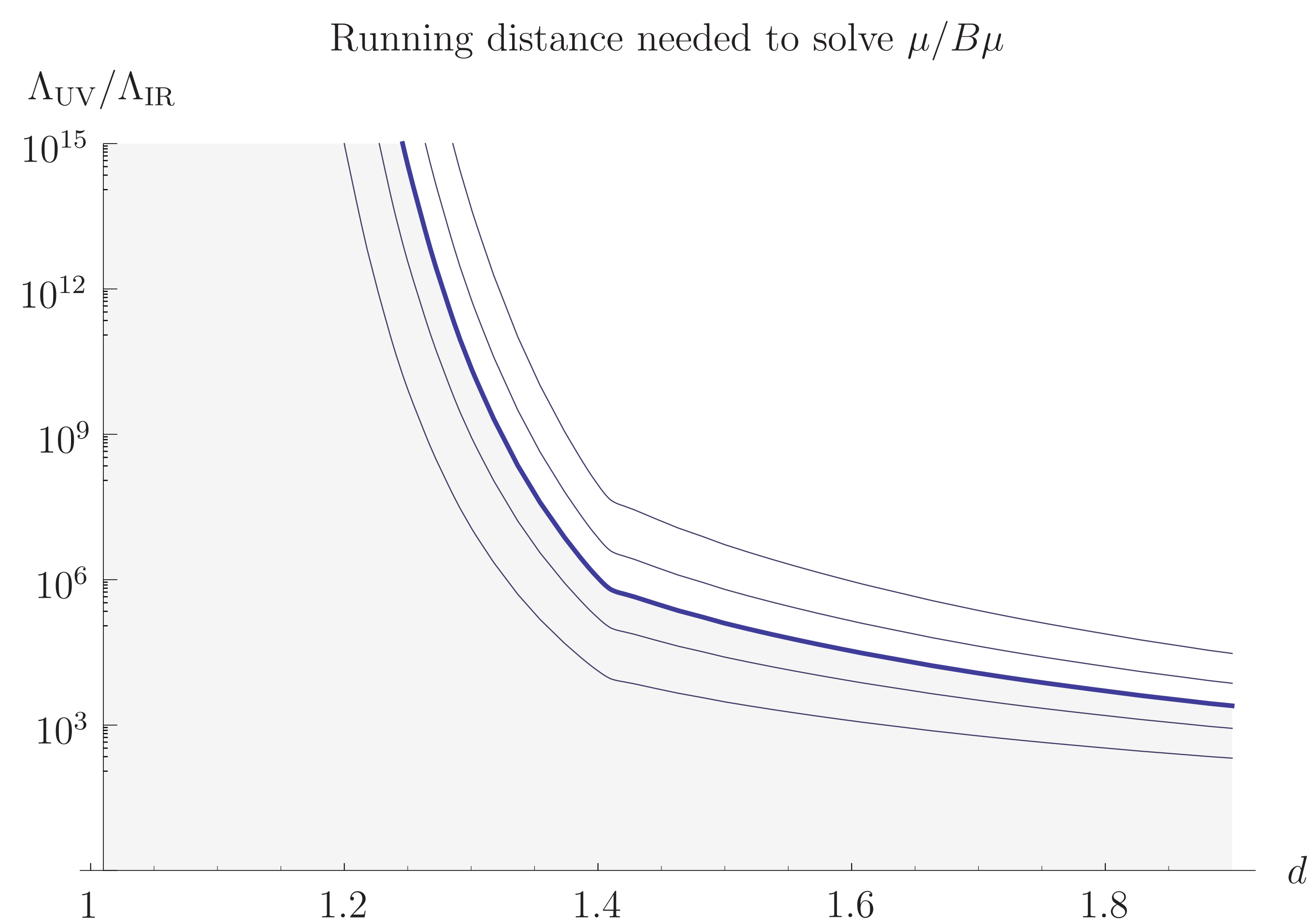
MSSM-messenger-messenger "Type I"

MSSM-MSSM-messenger "Type II"

The models with the best tuning are the type I squark models and the top-Yukawa-like type II models

Work in progress: investigating the constraints from flavor violation on these models.... (Evans, Thalapallil & DS)





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