SAVING SUSY

[Early hints about the status and nature of weak-scale supersymmetry]

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Based on arXiv:1206.1058 with A. Azatov, S. Chang, N. Craig

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AT ISSUE: THE HIGGS POTENTIAL

At tree-level...

$$\Delta V = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + \lambda_1 |H_u|^4 + \lambda_2 |H_d|^4 - 2\lambda_3 |H_u|^2 |H_d|^2$$

Quartics are CRUCIAL

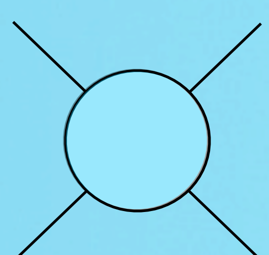
$$\boxed{\text{MSSM: } \lambda_1 = \lambda_2 = \lambda_3 = \frac{1}{8}(g^2 + g'^2)}$$

Two important results:

An obvious tension

$$m_h^{\text{tree}} \leq m_Z$$

$\Rightarrow \; m_h = 125\,\text{GeV}$ requires large contribution from SUSY *breaking*, e.g.



heavy stops

$\Rightarrow$ large $\delta\lambda_1$
large δm_h

A less obvious tension

A single asymmetry between the two Higgses:

$$m_{H_u}^2 \neq m_{H_d}^2$$

So the two angles of the Higgs sector - α and β - are not independent...

A lot known about the first, soon it'll be time to think harder about the second

GAME PLAN FROM HERE

Simple question of increasing relevance

Can we use the quartic structure and consequent information about couplings, comparing directly to data to tell us about feasibility and consistency of particular SUSY scenarios?*

*Assuming $m_{\mathrm{SUSY}} > m_h$

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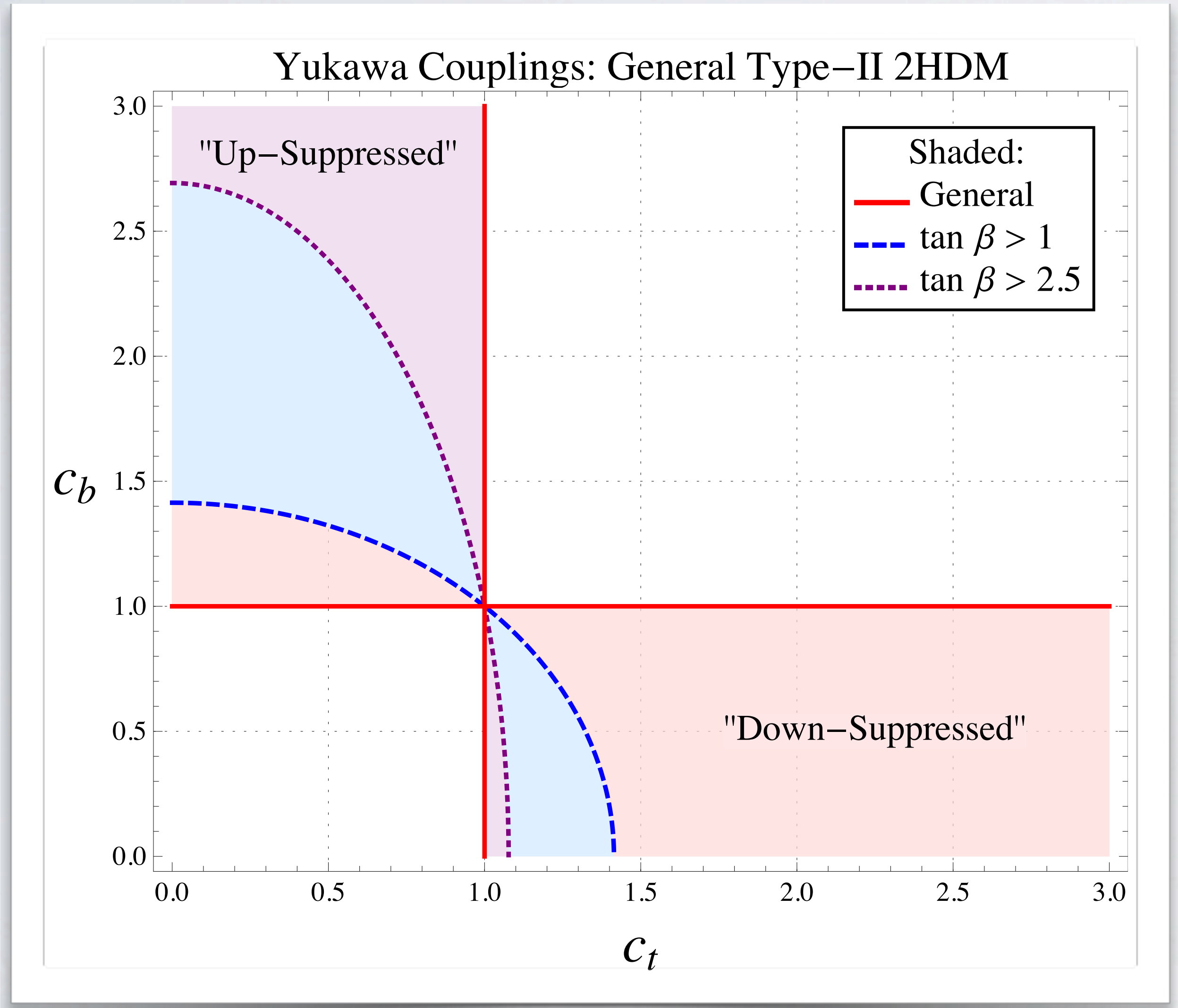
$$\mathrm{DATA} \overset{?}{\Leftrightarrow} \{\tan\beta, \lambda_i\}$$

TYPE-II 2HDM, THE GENERAL CASE

Now with all quartics turned on, and treated generically:

$$\Delta V = \lambda_1 \left|H_u^0\right|^4 + \lambda_2 \left|H_d^0\right|^4 - 2\lambda_3 \left|H_u^0\right|^2 \left|H_d^0\right|^2$$
$$+ \left[\lambda_4 \left|H_u^0\right|^2 H_u^0 H_d^0 + \lambda_5 \left|H_d^0\right|^2 H_u^0 H_d^0 + \lambda_6 (H_u^0 H_d^0)^2 + \text{c.c.}\right]$$

These feed into mass matrices, thus into couplings



Two distinct regions accessible in the up-down Yukawa plane

The lower region (suppressed down-type) requires some fancy footwork

$$\lambda_1 \sin^2\beta - \lambda_2 \cos^2\beta - \cos(2\beta)\lambda_3 + \frac{\sin 3\beta}{2\cos\beta}\lambda_4 + \frac{\cos 3\beta}{2\sin\beta}\lambda_5 < 0$$

(cf. Azatov et al, 1206.1058)

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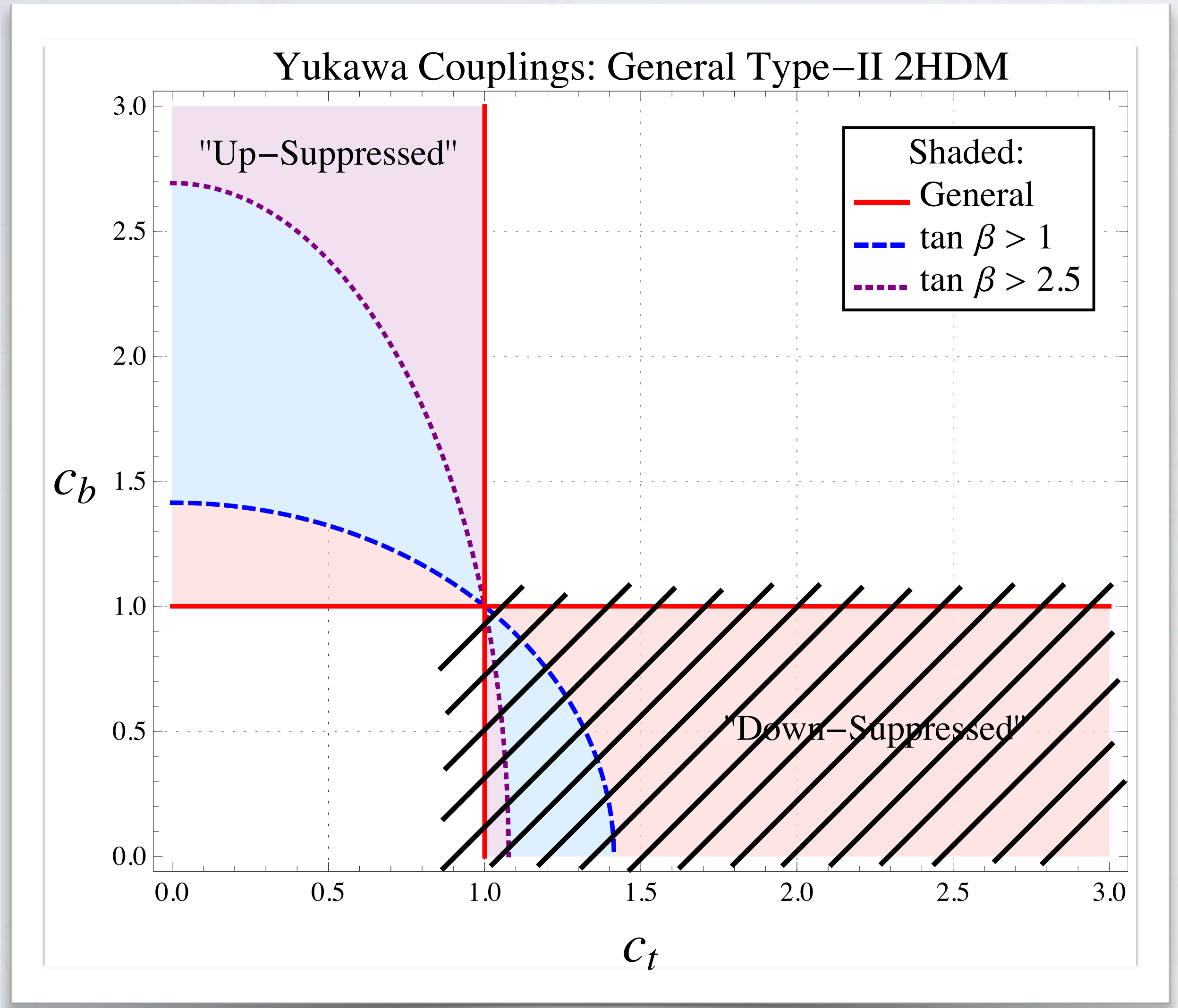

Two distinct regions accessible in the up-down Yukawa plane

e.g. unbroken MSSM:

$$(\lambda_1 + \lambda_3) \times v_u^2 < (\lambda_2 + \lambda_3) \times v_d^2$$

CONCLUSION: bottom is typically *enhanced* in MSSM (assuming $\delta\lambda_1$ large)

INTERLUDE: HIGGS FROM THE BOTTOM UP

[A simple framework for model-independent constraints]

Amend Higgsless SM with a custodial singlet scalar with arbitrary couplings:

$$\boxed{\begin{aligned}\Delta\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi \frac{h}{v} + \dots\right) \\ - \left(m_W^2 W_\mu W^\mu + \frac{1}{2}m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2a\frac{h}{v} + \dots\right)\end{aligned}}$$

(cf. Giudice et al, hep-ph/0703164)

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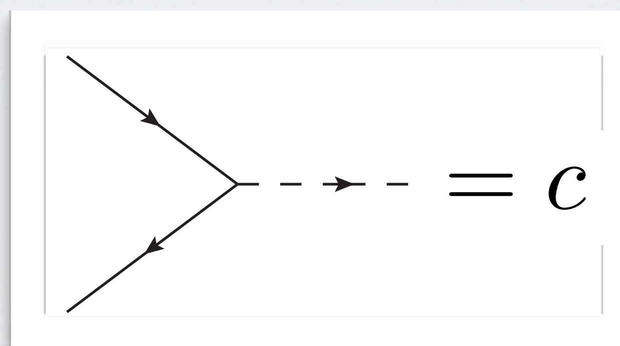

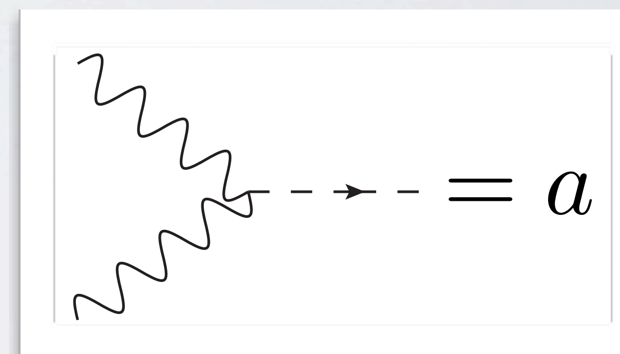

MSSM: $c_u = \frac{\cos\alpha}{\sin\beta}, \; c_d = \frac{-\sin\alpha}{\cos\beta}$ $\qquad a = \sin(\beta - \alpha)$

Now rescale production and branching; compare to limits and best fits for signal strength modifier from individual channels

SO WHAT DO THE DATA SAY?

	$R(a,c)$	$\hat{\mu}\|_{\mathrm{CMS}}$	$\hat{\mu}\|_{\mathrm{ATLAS}}$
$\gamma\gamma + 2j$	$a^2 r_{\gamma\gamma}$	3.6	—
$\gamma\gamma$	$c^2 r_{\gamma\gamma}$	1.1	2
$WW + 2j$	a^4	0	0
VV	$a^2 c^2$	0.6	0.8

(Nicely summarized by Farina et al, 1205.0011)

$$r_{\gamma\gamma} \simeq (1.26a - 0.26c)^2$$

WHAT DO THE THEORISTS SEE?

	$R(a,c)$	$\hat{\mu}\vert_{\mathrm{CMS}}$	$\hat{\mu}\vert_{\mathrm{ATLAS}}$
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Significant tension between channels most sensitive to the vector coupling; let's take this at face value and run with it...

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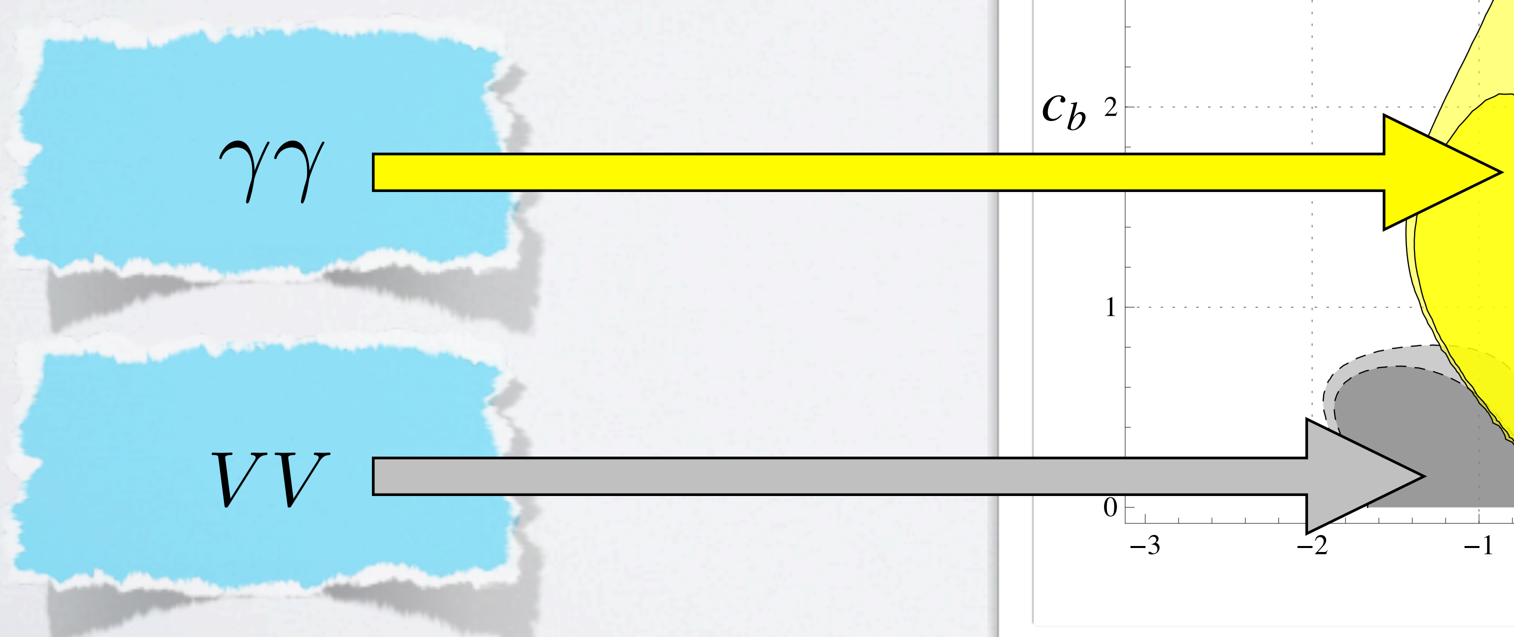

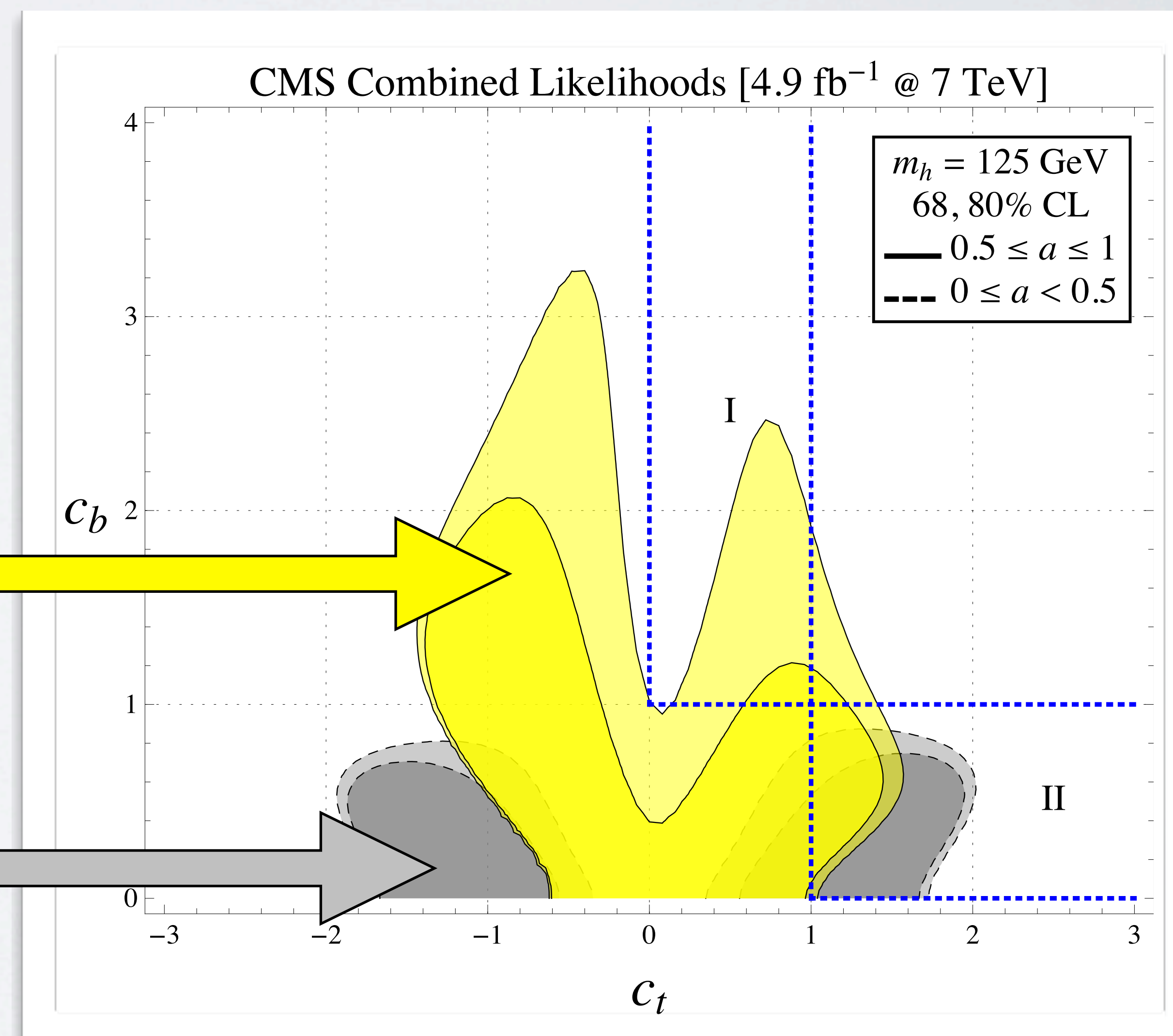

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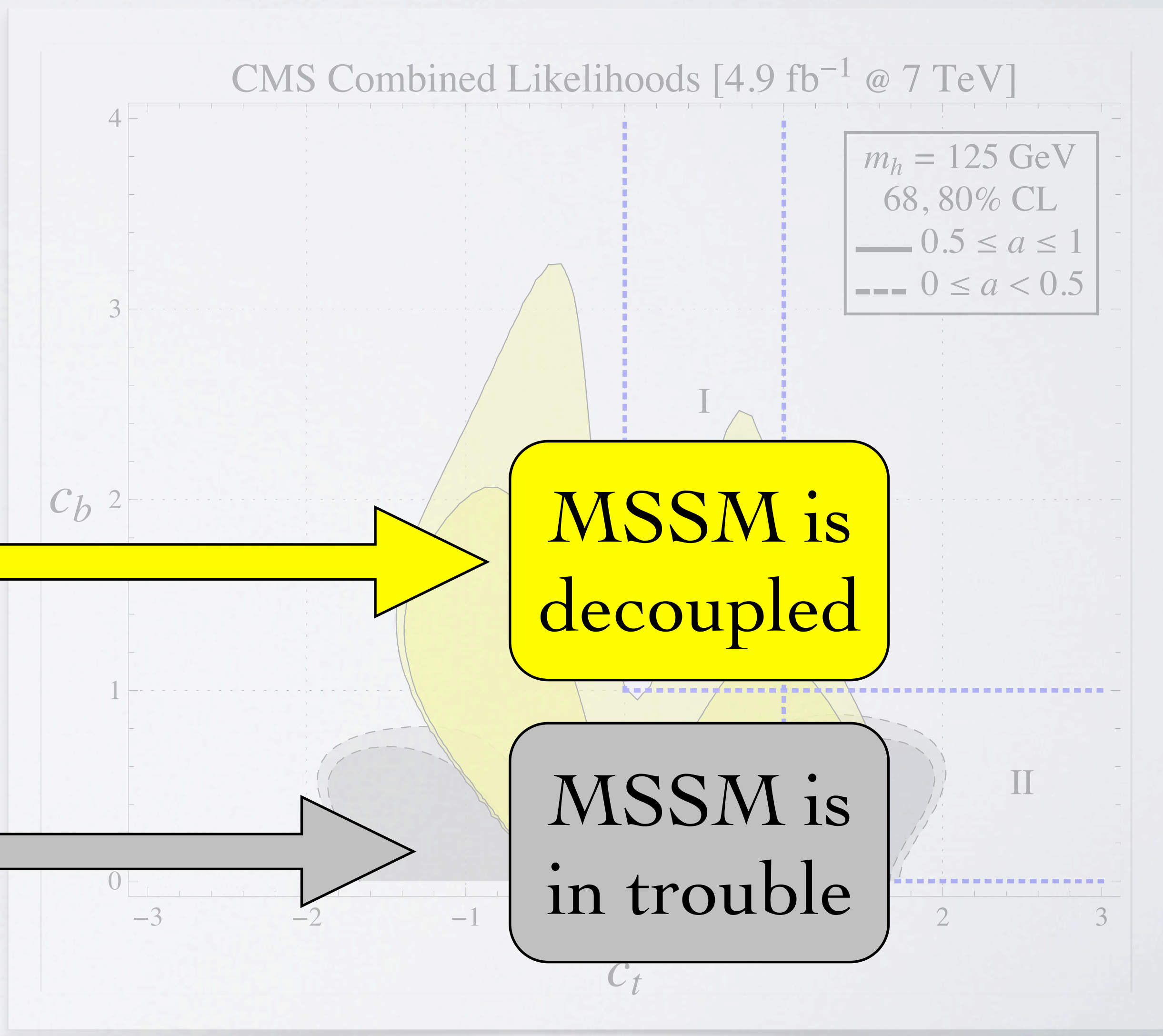

MSSM is decoupled

MSSM is in trouble

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...What if VV is telling the truth (at least partially)?

ESCAPE HATCHES IN THE (X)MSSM

[eXtra stuff]

Recall the general potential:

$$\Delta V = \lambda_1 \left|H_u^0\right|^4 + \lambda_2 \left|H_d^0\right|^4 - 2\lambda_3 \left|H_u^0\right|^2 \left|H_d^0\right|^2 + \left[\lambda_4 \left|H_u^0\right|^2 H_u^0 H_d^0 + \lambda_5 \left|H_d^0\right|^2 H_u^0 H_d^0 + \lambda_6 (H_u^0 H_d^0)^2 + \text{c.c.}\right]$$

With bottom suppression at largish tan beta possible when

$$\lambda_1 + \lambda_3 - \frac{\lambda_4}{2} \tan\beta \lesssim 0$$

MSSM

e.g. effects from stops:

$$\delta\lambda_1 = \frac{3y_t^4}{16\pi^2}\left[\left(\frac{A_t}{m_{\tilde{t}}}\right)^2 - \frac{1}{12}\left(\frac{A_t}{m_{\tilde{t}}}\right)^4\right]$$

$$\delta\lambda_3 = \frac{3y_t^4 \mu^2}{64\pi^2 m_{\tilde{t}}^2}\left[\left(\frac{A_t}{m_{\tilde{t}}}\right)^2 - 2\right]$$

$$\delta\lambda_4 = \frac{y_t^4 \mu}{32\pi^2 m_{\tilde{t}}}\left[\left(\frac{A_t}{m_{\tilde{t}}}\right)^3 - \frac{6A_t}{m_{\tilde{t}}}\right]$$

(cf. Carena et al, hep-ph/9504316)

Possibilities remain (e.g. staus)...

(cf. Carena et al, 1112.3336 & 1205.5842)

NMSSM, etc.

$$W = \lambda S H_u H_d + f(S)$$

$$\Rightarrow \delta\lambda_3 = -|\lambda|^2/2$$

(cf. lots of stuff...)

inequality can be turned around, provided coupling is largish:

$$\lambda \gtrsim 0.6$$

approaching Fat Higgs territory, especially in the presence of non-light stops; again possibilities remain...

DEMOTING THE QUARTICS

[Possible escape hatch in case a b-suppressed balance is struck]

Can we arrange something simpler than usual? One possibility:

$$\Delta\mathcal{L} \sim \Lambda^3 H - m^2 H^2$$

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But this comes from something we know well: Higgs from a "magnetic sector"

(cf. Craig et al, 1106.2164; Azatov et al, 1106.3346; Gherghetta et al, 1107.4697; Heckman et al, 1108.3849...)

	$SU(2)$	$SU(2)_i$
Q_i	$\square$	$\square$
H_{ij}	1	$(\square, \square)$

$$\Delta W = \lambda HQQ$$

- Minimal confining gauge group
- $i = 1, \ldots, 4$; $1 \to L$, $2 \to R$
- 2N flavors: self-dual, strong F.P.

- Assume no SUSY mass for $Q_{1,2}$
- ~~SUSY~~ $\Rightarrow$ confines @ $\Lambda_{\mathrm{M}} \lesssim \Lambda_{\mathrm{SUSY}}$

$$\Rightarrow \quad \Delta V = m^2_{H_{u,d}} |H_{u,d}|^2 + \left(c \frac{\lambda_{u,d}\Lambda^3_{\mathrm{M}}}{16\pi^2} H_{u,d} + \text{h.c.} \right) + \ldots$$

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> 0

$$v = c \frac{\lambda \Lambda_{\mathrm{M}}^3}{16\pi^2 m^2} > f_{\mathrm{M}}$$

$\lambda \Rightarrow \tan\beta$

$m \Rightarrow$ mass, α

IMPLICATIONS

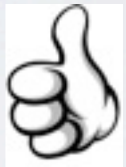
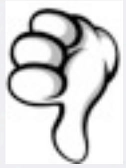
1. We don't even *need* the quartics

   $\Rightarrow$ Nothing fancy (no tuning) needed in order to attain $m_h \gg m_Z$

   $\Rightarrow$ Nothing fancy (large A terms, mixings, ...) for $c_b \to 0$ as $\tan\beta \to \infty$

2. The magnetic sector contains lightish scalars. Minimally $[SU(2)^2/SU(2)]$:

$$m^2_{\vec{\pi}} \sim (\lambda_u v_u + \lambda_d v_d)\Lambda_{\rm M} \left\{ \begin{array}{l} \text{e.g.} \quad \Lambda_{\rm M} = \text{TeV}, \;\text{large}\; \tan\beta, \; m_h = 125\,\text{GeV} \\ \qquad \Rightarrow m_\pi \sim 350\,\text{GeV}, \; \lambda_u v_u/\Lambda_{\rm M} \simeq 0.1 \\ \text{Decays to heavy SM states: } \pi^0 \to t\bar{t}, \; Zh^0 \end{array} \right.$$

3. Theoretical aspects:
   - Naturalness fully restored (frees up Higgs, stops as well) 
   - Unification certainly not automatic, but *can* be done 
   - Dark matter: nothing to add. 

CONCLUSIONS

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Meanwhile:

- A potentially relevant portion of the Yukawa parameter space can be reopened by careful conspiracy among (x)MSSM parameters...

$$\Delta W = \underbrace{\lambda S H_u H_d}_{\text{(singlets)}},\ \underbrace{\lambda H \mathcal{O}}_{\text{(doublets)}},\ \underbrace{\lambda T H_u H_u}_{\text{(triplets)}},\ \ldots$$

  ...can all be encoded in the Higgs potential and compared directly to measured couplings

- Mass at 125 and couplings with any bottom suppression amount to a tense situation for minimality; non-minimal dynamics might be preferred

- A "Magnetic Higgs" gives us a lot of breathing room, and plenty of new states (scalars of the strong dynamics, light stops...) to anticipate.

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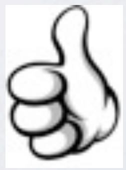

BACKUPS

FLAT/RUNAWAY DIRECTIONS

Without SUS'ic masses for EW Q states, we need to worry about runaways:

$$\mathcal{L} = \int d^4\theta \underset{(1)}{\mathcal{Z}} Q^\dagger \underset{(2)}{e^F} \underset{(3)}{e^V} Q + \ldots$$

1) Contains physical gauge coupling and flavor-universal soft masses (D term)
2) Imagine gauging the non-anomalous flavor symmetries, F
3) Usual gauging.

- Flavor-universal mass suppressed in IR for attractive IR fixed point
- Masses proportional to 'gauged' flavor symmetries not renormalized; tachyonic terms will exist
- Coupling to H lifts flat directions...

- H joins fixed point only in the IR...
- ...any flat directions lifted by *its* soft mass!

THE PERTURBATIVE REGIME

$$\Delta\mathcal{L}_{\text{eff}} = -m^2 |H|^2 + \sum_i \frac{c\Lambda^{4-i}}{16\pi^2} \text{tr}\left[\left(\Sigma^\dagger \mathcal{H}\lambda\right)^i\right] + \ldots$$

$$\Delta\mathcal{L}_{\text{UV}} = \lambda H Q\bar{Q}$$

Back-reaction of Higgs VEV
resembles a technifermion mass

Effective theory's logical limit (predictive regime)

$$\lambda v \ll \Lambda_{\text{M}}$$

or

$$\frac{\lambda}{4\pi}\frac{v}{f_{\text{M}}} \ll 1$$