The SUSY Twin Higgs

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GGI, Florence
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based on **work in progress**

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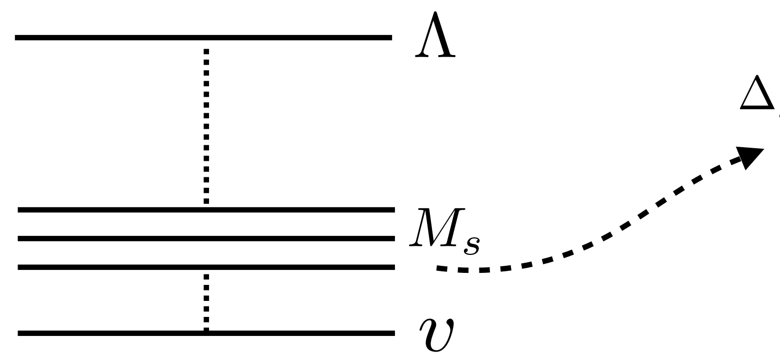
Why a SUSY Twin Higgs?

SUSY needs some help with 3 issues:

LITTLE FINE-TUNING PROBLEM



$$\Delta_{SUSY} = \frac{3y_t^2 M_s^2}{2\pi^2 m_h^2} \log \frac{\Lambda}{M_s} \sim 100$$

HIGGS MASS

extra non-decoupled quartic is needed to get $m_h = 125$ GeV

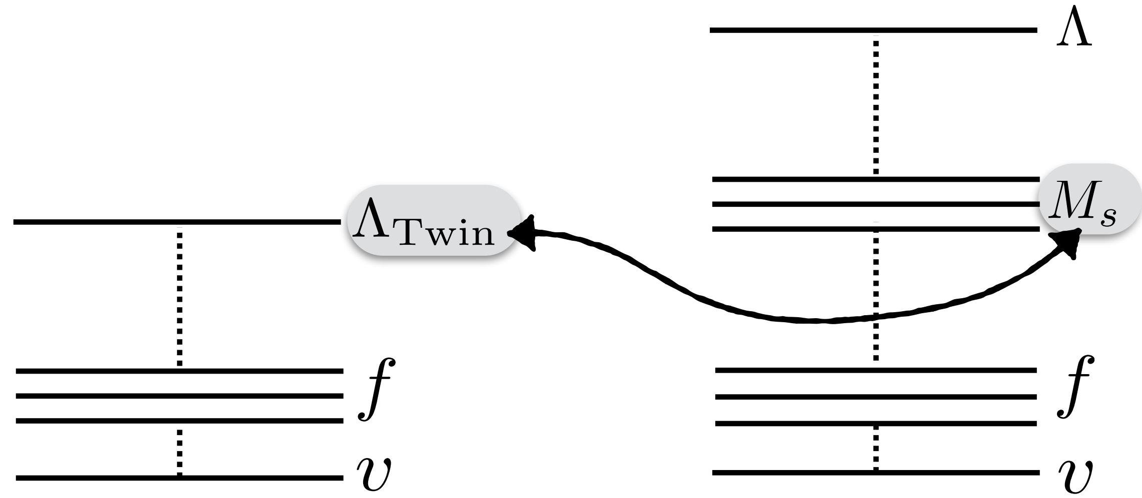
ex. NMSSM $m_h^2 = m_z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2$

WHERE IS EVERYBODY?

M_s controls the scale of colored states

Twin Higgs needs a UV completion:

what happens if
$\Lambda_{\text{Twin}} = M_s$
?



(mild)
GAIN in FINE-TUNING

$$\Delta_{\text{Twin-SUSY}} \sim \frac{1}{\lambda}\Delta_{\text{SUSY}}$$

1312.1341
Craig & Howe

λ controls the accidental symmetry making the Higgs a PGB

HIGGS MASS

It is typically heavier than in the MSSM

Neutral Naturalness

The Twin sector dynamics at $\sqrt{\lambda} f$ is Neutral under the SM

0506256
Chacko, Goh and Harnik

Twin SUSY

“ Twin Higgs ”

Higgs is PGB of accidental global symmetry from explicit Z2 symmetry

top partners uncolored

ameliorates fine-tuning

provides calculable UVC

Supersymmetry

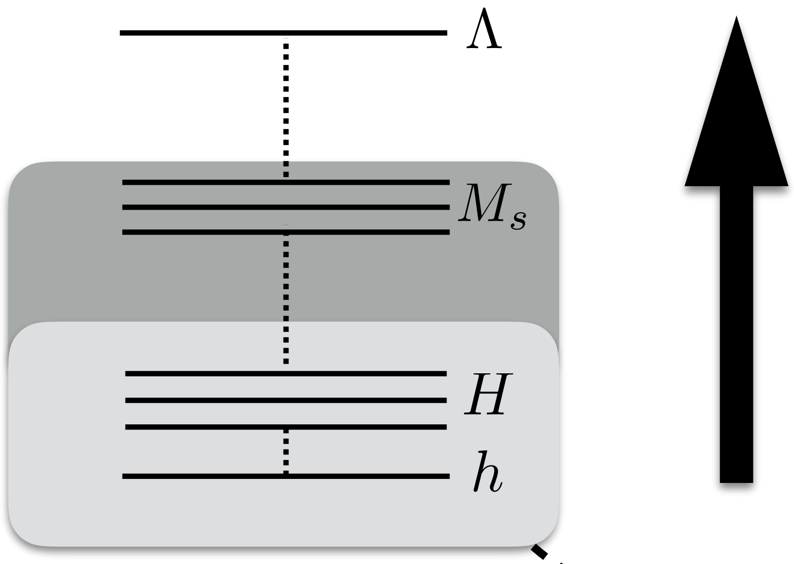
calculability,
gauge coupling unification

Only few existing models (tuning 1-2 %)

0604076 Chang, Hall & Weiner
0604066 Falkowski, Pokorski & Schmaltz
1312.1341 Craig & Howe

Explore general structure and identify new promising directions
(tuning 10 - 20 % !?)

Plan of the TALK



Understanding Twin SUSY
from the bottom up…

1) A fresh look to the Twin Higgs

2) SUSY implementations

3) sketching the phenomenology
of the extended Higgs sector

higgs couplings

VS

direct searches
of extra Higgses

A fresh look to the Twin Higgs

Twin Higgs: **Setup**

Double SM gauge fields, Higgs and tops

$$G_{\rm SM} \quad \to \quad G^A_{\rm SM} \quad \times \quad G^B_{\rm SM}$$

$$H, Q_3, U_3 \quad \to \quad \underbrace{H_A, Q_{3A}, U_{3A}}_{\text{visible sector}} + \underbrace{H_B, Q_{3B}, U_{3B}}_{\text{“dark” sector: neutral under SM!}}$$

Natural Z_2 exchange symmetry: $\quad H_A \longleftrightarrow H_B \quad \ldots$

the role of Z_2

- Z_2 involves the full SM **0509242 Barbieri, Hall & Gregoire**
- Minimal (“fraternal”) Twin Higgs; double only fields most relevant for naturalness + add what is needed for anomaly cancellation

1501.05310 Craig, Katz, Strassler & Sundrum

Affect a lot of phenomenology but
we leave it unspecified in our discussion...

Linear sigma model

$$V_H(H_A, H_B) = \underbrace{V_H^{U_4}}_{} + \underbrace{V_H^{\not{U}_4, Z_2}}_{} + \underbrace{V_H^{\not{U}_4, \not{Z}_2}}_{}$$

depends only on $\mathcal{H} = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$

respects $H_A \leftrightarrow H_B$

respects only gauge symmetry

U_4 part dominant, negative mass term

$$V_H^{U_4} = \lambda \left(|H_A|^2 + |H_B|^2 - f^2 \right)^2$$

Dark Higgs gets large U_4 breaking vev

$$|H_B|^2 = f^2 - |H_A|^2$$

7 GB - 6 eaten visible/dark gauge bosons = SM Higgs $\approx H_A$

Twin Higgs: **radiative corrections**

Radiative corrections mainly from top sector

$$V_{\text{Yuk}} = y_{tA} Q_A U_A H_A + y_{tB} Q_B U_B H_B$$

$$\Delta V_{top} = -\frac{3}{16\pi^2}\left[y_{tA}^2|H_A|^2\Lambda_t^2 + y_{tB}^2|H_B|^2\Lambda_t^2 - y_{tA}^4|H_A|^4\log\frac{\Lambda_t^2}{m_{tA}^2} - y_{tB}^4|H_B|^4\log\frac{\Lambda_t^2}{m_{tB}^2}\right]$$

Twin Higgs: **radiative corrections**

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Impose Z_2 invariance

$y_{tA} = y_{tB} = y_t$

$$y_t^2 \left[|H_A|^2 + |H_B|^2\right] \Lambda_t^2$$

$$y_t^4 \left[|H_A|^4 + |H_B|^4\right] \log \Lambda_t^2$$

Twin Higgs: **radiative corrections**

Radiative corrections mainly from top sector

$$V_{\rm Yuk} = y_{tA} Q_A U_A H_A + y_{tB} Q_B U_B H_B$$

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Impose Z_2 invariance
$y_{tA} = y_{tB} = y_t$

$$y_t^2 \left[|H_A|^2 + |H_B|^2 \right] \Lambda_t^2$$

U$_4$ invariant! $\delta f \sim \Lambda_t / 4\pi$

$$y_t^4 \left[|H_A|^4 + |H_B|^4 \right] \log \Lambda_t^2$$

SM quartic+mass term
$\delta m_h \sim f/4\pi$

UV cutoff enlarged by loop factor $\delta m_h \sim f/4\pi \sim \Lambda_t/(4\pi)^2$

The B-states are neutral under SM

0506256
Chacko, Goh and Harnik

Twin Higgs: **EWSB**

$$V_H(H_A, H_B) = \underbrace{V_H^{U_4}}_{\lambda\left(|H_A|^2+|H_B|^2-f^2\right)} + \underbrace{V_H^{\not{U}_4, Z_2}}_{\kappa\left[|H_A|^4+|H_B|^4\right]} + \underbrace{V_H^{\not{U}_4, \not{Z}_2}}_{\rho|H_A|^4+\sigma f^2|H_A|^2}$$

$\rightarrow |H_B|^2 = f^2 - |H_A|^2$ loops tree

hard Z2 breaking ($\rho|H_A|^4$)

soft Z2 breaking ($\sigma f^2|H_A|^2$)

Match to SM Higgs potential

$$V_{eff} \sim -f^2\left(k+\frac{\sigma}{2}\right)H^2 + \frac{1}{6}\left(4k+\frac{\sigma+\rho}{2}\right)H^4$$

need explicit Z2 breaking

SOFT: tune $\sigma \sim -2k$

this is what was mostly studied so far

HARD: $\sigma \sim \rho\frac{\Lambda_\rho^2}{4\pi^2 f^2}$

quartic > mass $\Lambda_\rho < 2\pi f$

Twin Higgs: **EWSB**

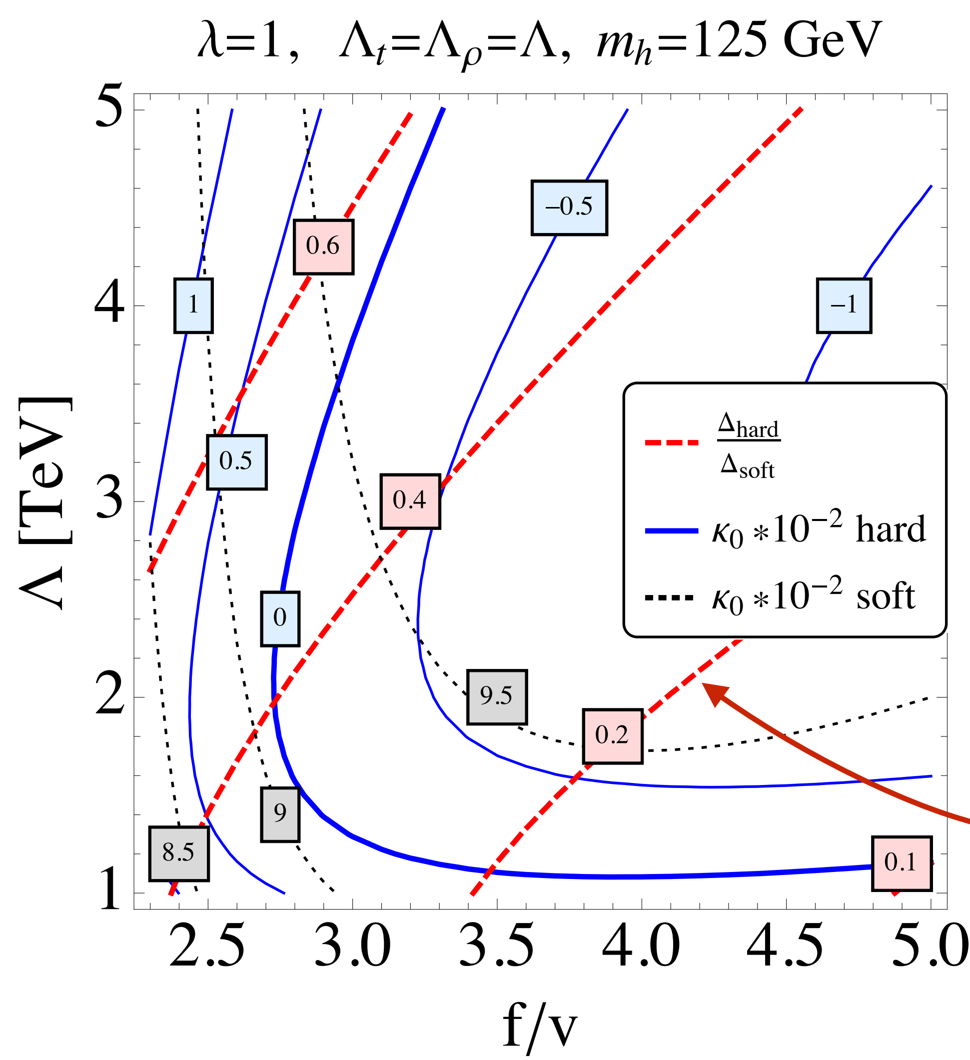
$$V_{\rm eff} \sim -f^2 \left(\frac{\kappa}{(4\pi)^2} + \sigma \right) H^2 + \left(\frac{\kappa}{(4\pi)^2} + \sigma + \rho \right) H^4$$

	soft Z2 breaking	hard Z2 breaking
EW scale	$\frac{v^2}{f^2} = \frac{1}{2}\left(1 - \frac{\sigma}{2k}\right)$	$\frac{v^2}{f^2} = \frac{1}{2}\left(\frac{k - \frac{\rho\Lambda_\rho^2}{8\pi^2 f^2}}{\rho}\right)$
Tuning	$\Delta^{\rm soft}_{v/f} \approx \frac{f^2}{2v^2}$	$\Delta\vert^{\rm hard}_{v/f} \approx \left(\frac{\Lambda_\rho}{4\pi v}\right)^2$
Higgs Mass	$m_h^2\vert_{\rm soft} = 2\sqrt{2\kappa}v$	$m_h\vert_{\rm hard} \approx 2\sqrt{\kappa} f \left(\frac{4\pi v}{\Lambda_\rho}\right)$

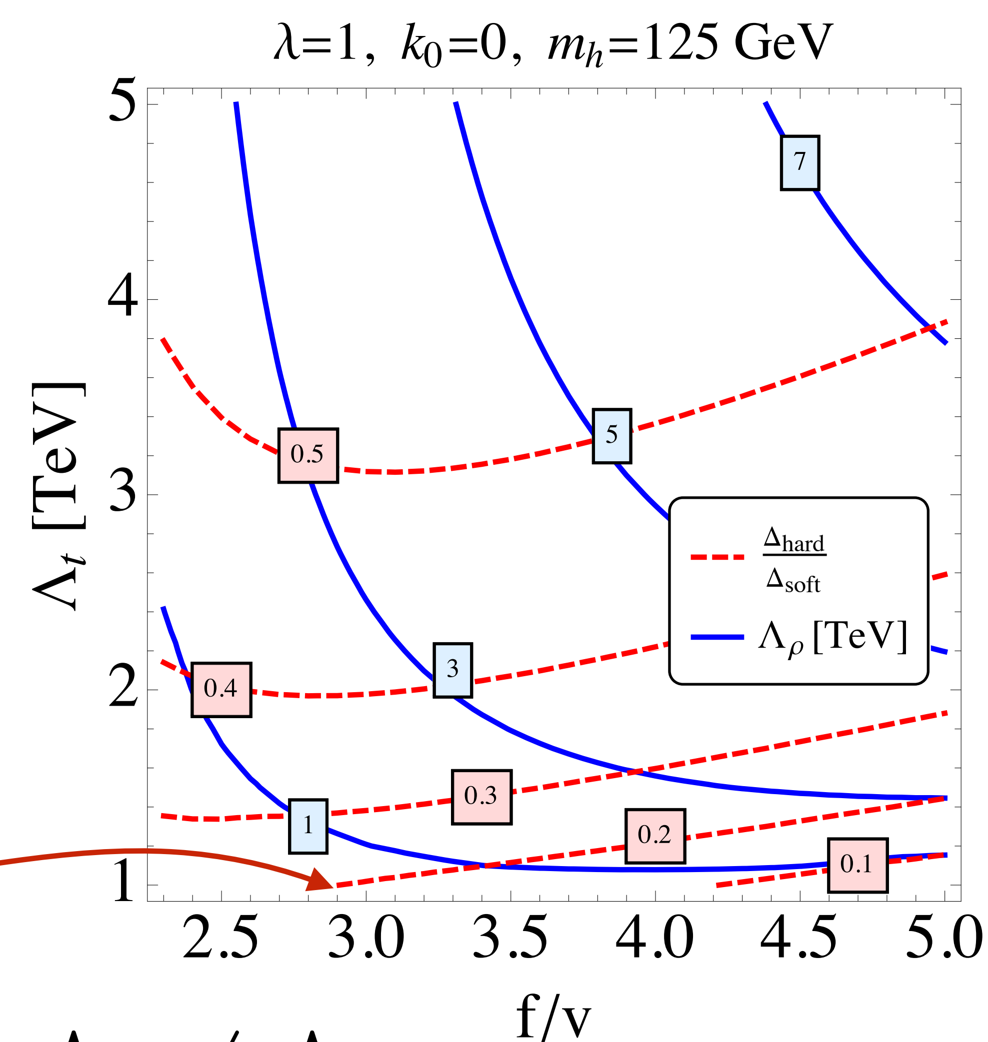
Hard breaking model is sensibly less fine tuned if $\Lambda_\rho < 2\pi f$ $\longrightarrow$ who is Λ_ρ ?

The Higgs mass increases by the same amount $\longrightarrow$ small κ ?

hard vs soft *in summary*



gain in fine-tuning up to a factor of 5-10



$\Lambda_\rho \sim \Lambda_t$ overshoots the Higgs

$\Lambda_\rho \neq \Lambda_t$

WAYS OUT:

small f & low Λ_t	challenged by Higgs coupling & direct searches
$k_0 < 0$	negative quartic to reduce the Higgs mass?

the cut-off of the Higgs loop can correspond to uncoloured states?

see later...

Twin SUSY

matching the SUSY potential to the Twin Higgs linear sigma model

$$h_u^A = H_A s_A \qquad h_d^A = H_A^\dagger c_A$$

$$h_u^B = H_B s_B \qquad h_d^B = H_B^\dagger c_B$$

Get large U_4 preserving quartic from non-decoupling F-term of singlet

$$W = \lambda_S S \mathcal{H}_u \mathcal{H}_d$$

$$\downarrow \; m_S \gg M_S$$

$$V^{U_4} = m_u^2 |\mathcal{H}_u|^2 + m_d^2 |\mathcal{H}_d|^2 b\left(\mathcal{H}_u \mathcal{H}_d + c.c\right) + \lambda_S |\mathcal{H}_u \mathcal{H}_d|^2$$

matching

$$V_H^{U_4} = \lambda\left(|H_A|^2 + |H_B|^2 - f^2\right)^2 \quad \begin{cases} \lambda = \frac{\lambda_S^2}{4}\, s_{2A} s_{2B} \approx \frac{\lambda_S^2}{4} s_{2\beta}^2 \\ f^2 \approx -\frac{2}{\lambda_S^2 s_{2\beta}^2}\left(m_u^2 s_\beta^2 + m_d^2 c_\beta^2 - b\, s_{2\beta}\right) \end{cases}$$

In the full 4 Higgs doublet model there are two more EWSB conditions fixing

$$\begin{cases} t_\beta \\ \delta t_\beta = t_A - t_B \end{cases}$$

we can reliably compute the fine-tuning
with respect to the UV cut-off

We want to stay agnostic with respect to the origin of Z_2 -breaking $\Lambda = 100 M_s$

Two sources of tuning

$$\underbrace{f/M_S}$$

U_4 , similar NMSSM tuning v → f

$$\Delta_f \sim \frac{\delta m^2_{H_u}}{2\lambda^2 f^2 c^2_\beta}$$

$$\underbrace{v/f}$$

U_4 breaking, model-dependent

$f^2/2v^2$ / $(\Lambda_\rho/4\pi v)^2$

origin of explicit Z2 breaking:

- **soft** via gauge mediation
- **hard** via non-decoupled F-term $\begin{cases} W = \tilde{\lambda}\tilde{S}H_u^A H_d^A \quad m_{\tilde{S}} \gg M_{\tilde{S}} \\ \Lambda_\rho \approx M_{\tilde{S}} \end{cases}$

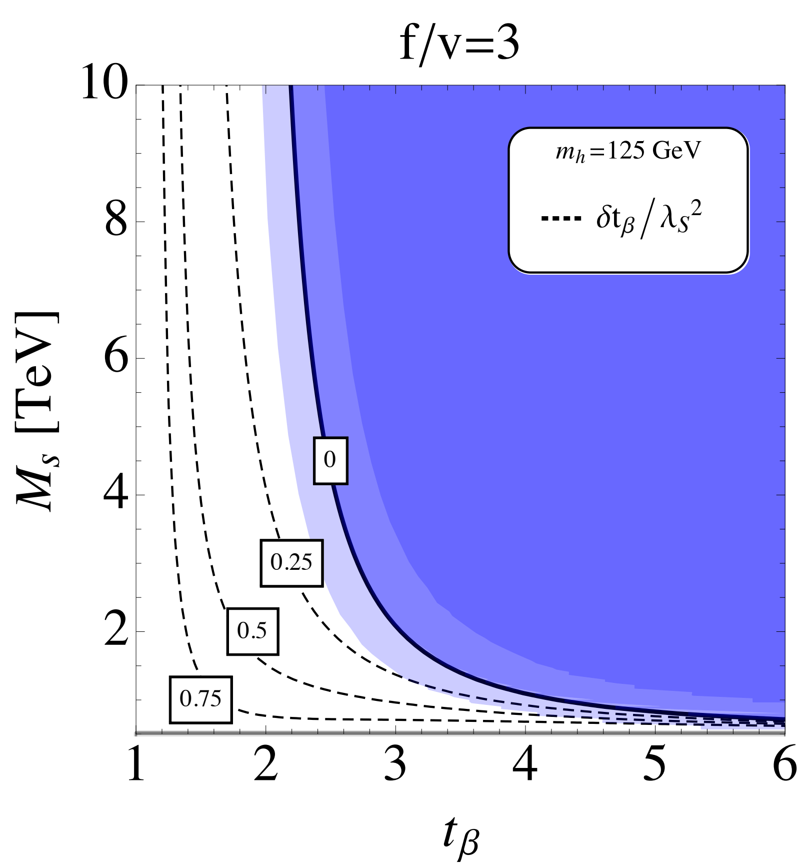
we can reliably compute the Higgs mass at 1-loop

$$m_h = 125 \pm 5 \text{ GeV}$$

(large theory uncertainty to be fixed including gluino contributions @ 2-loops)

$$\kappa \approx \frac{g^2 + g'^2}{8} c_{2\beta}^2 + \frac{3 y_t^4 s_\beta^4}{16\pi^2} \log \frac{M_s^2}{y_t^2 s_\beta^2 f^2} - \delta t_\beta \frac{\lambda_S^2}{4} s_{4\beta} c_\beta^2$$

D-terms   stop-top loops   F-terms



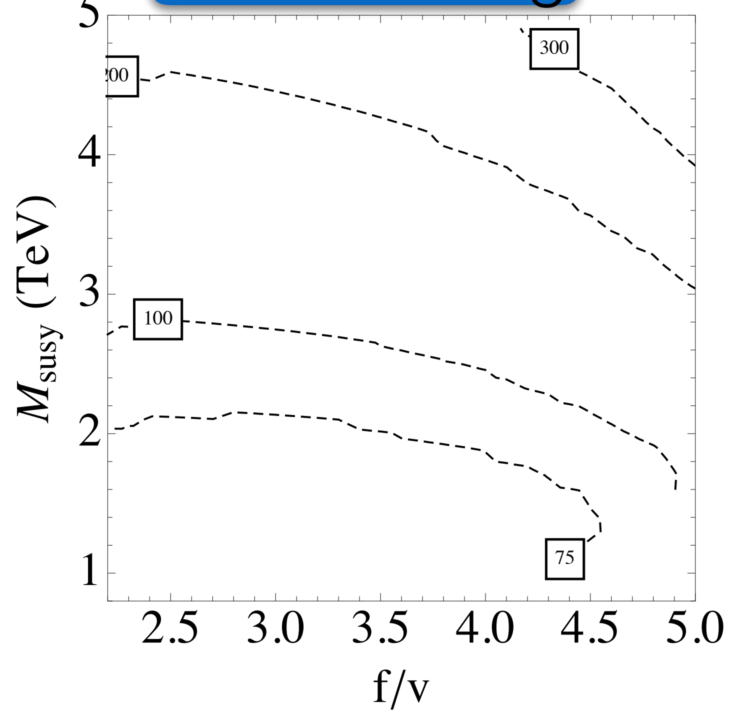
strong upper bound on

t_β and δt_β

the bounds get even stronger if we have hard-breaking…

$$m_h^2 \approx 8v^2 \left(\kappa + \frac{\rho}{2}\right)$$

soft-breaking



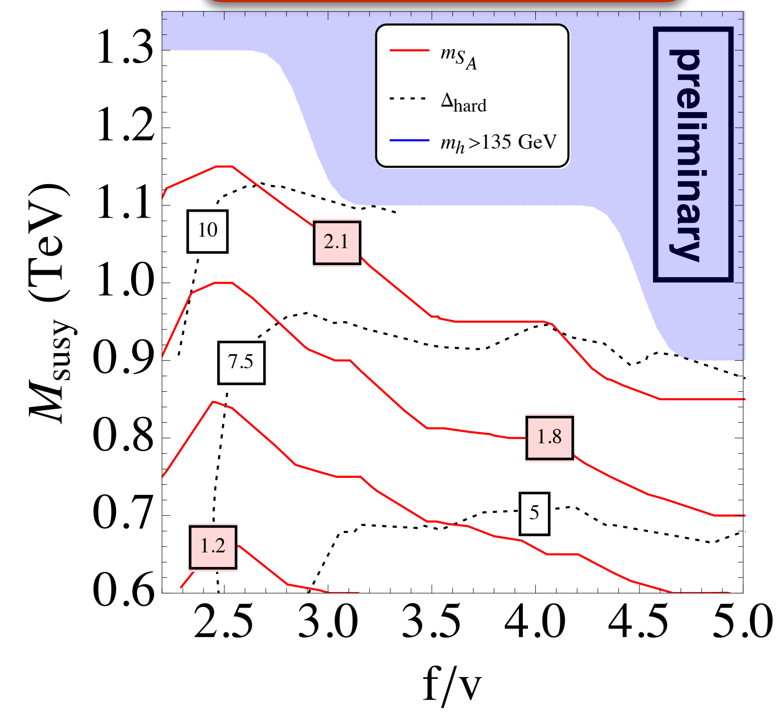
1% tuning

colored states decoupled from LHC

1312.1341 Craig & Howe

VS

hard-breaking



10% tuning

colored states within the reach of LHC
because of the Higgs mass constraint

negative quartic in SUSY?

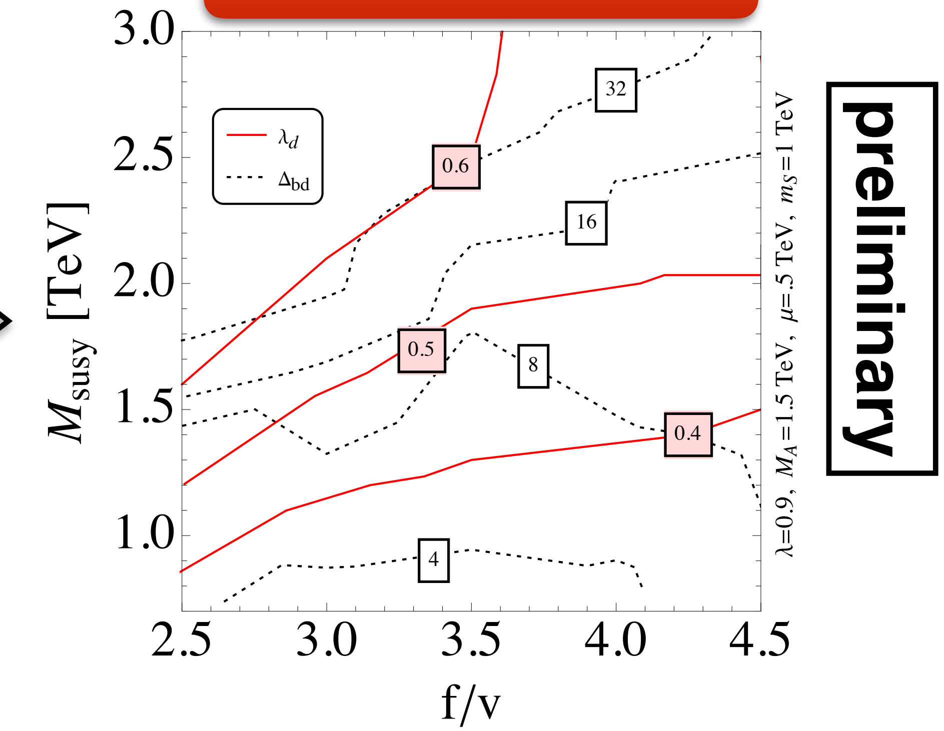
ugly example…

$$W = \lambda_d \Phi_d^{AB} H_u^A H_u^B$$

$$m_{\Phi_d} \gg M_{AB}$$

$$\kappa \to \kappa - \lambda_d^2 s_\beta^4$$

hard-breaking+AB bi-doublet



Extra Higgses

We have a full 4 Higgs doublet model

The structure of the spectrum

$m_A \quad f$

2 mass parameters + angles

$\} \; A_2^0 \;\; H_2^0 \;\; H_2^\pm \;\; \sim m_A$

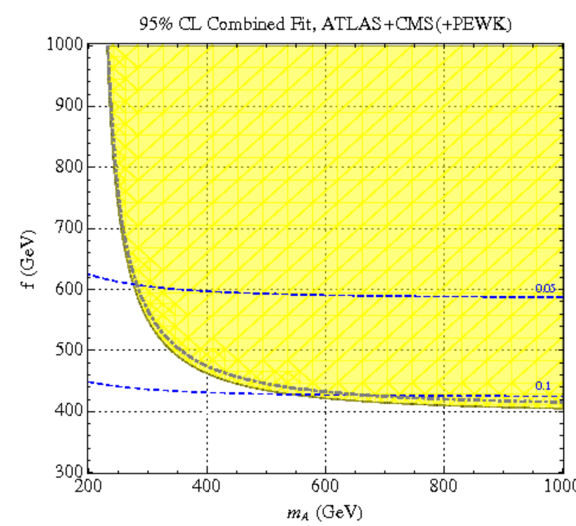
$\} \; A_1^0 \;\; H_1^0 \;\; H_1^\pm \;\; \sim \sqrt{m_A^2 - \lambda f^2}$

$h_2^0 \qquad \sim \sqrt{\lambda} f$

h

Higgs coupling constraints work like in the usual Twin Higgs

$$f > 2.2v$$



1312.1341 Craig & Howe

bound dominated by ZZ & WW coupling measurement

CAN WE OBSERVE THE EXTRA HIGGSES?

$h_2^0 \sim \sqrt{\lambda} f$ 1505.05488 Buttazzo, Sala & Tesi

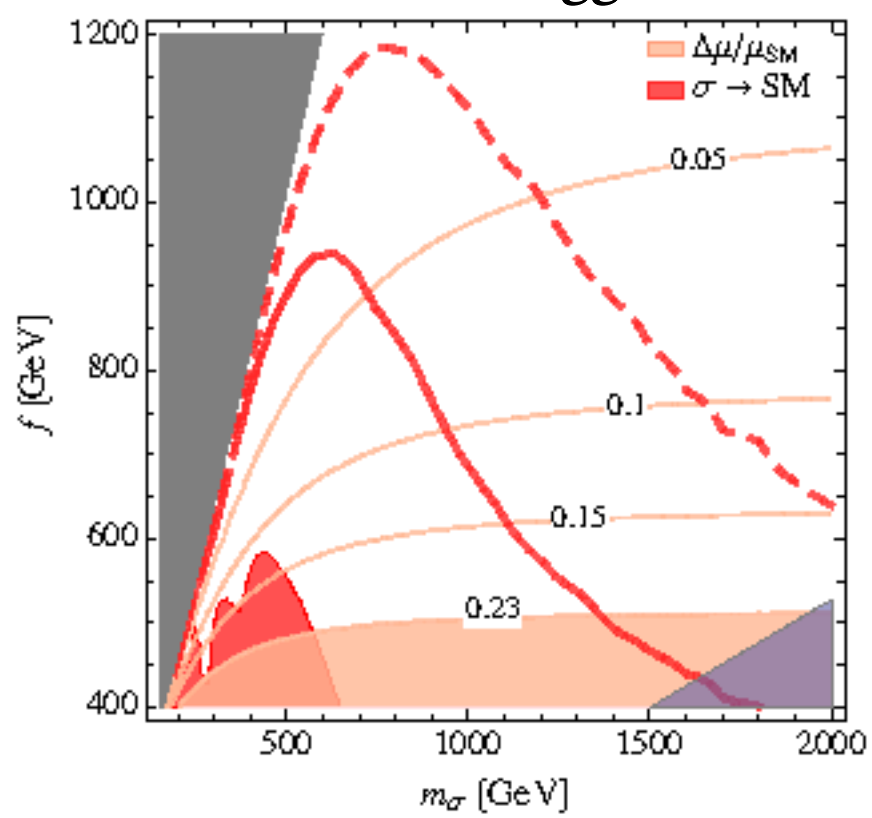
$A_1^0 \;\; H_1^0 \;\; H_1^\pm \sim \sqrt{m_A^2 - \lambda f^2}$ 1504.04630 Craig, D'Eramo, Draper, Thomas, Zhang

Colored states are decoupled

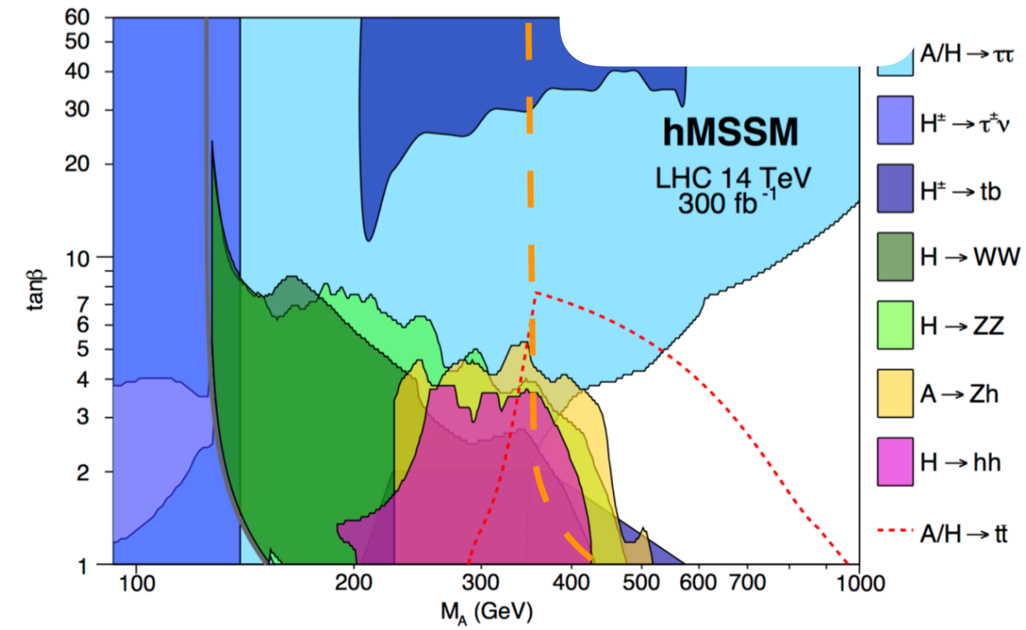
extra Higgses become smoking guns of these construction

Searches for singlet Higgses
&
charged/CP-odd Higgses

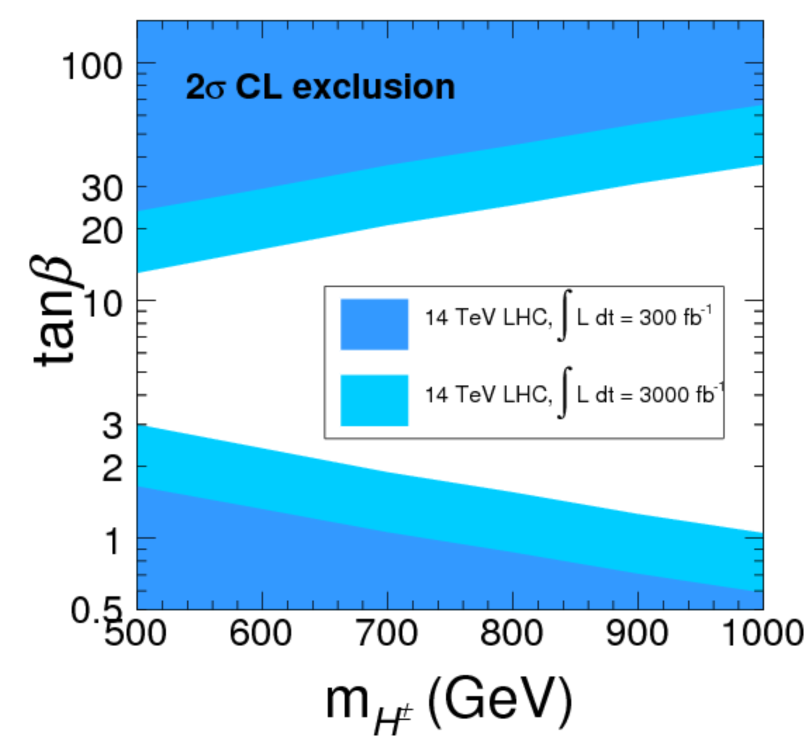
Twin Higgs



CP-odd



charged Higgses



The invisible BR is highly model dependent

$t_\beta < 2 - 3$ makes life harder

what we learned...

- Twin Higgs models can stabilize weak scale up to few TeV
- SUSY provides UV completion with calculable observables: "Twin SUSY"
- Systematic understanding by matching to the Twin Higgs
- Hard Z_2 breaking models allow for natural v/f hierarchies & they have SUSY realizations

what is left...

- Can one relate Z_2-breaking with SUSY-breaking?
- Hunting for the least fine-tuned perturbative model?
- New fraternal phenomenology? Cosmology?