A systematic approach to Twin SUSY Models

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work in progress with
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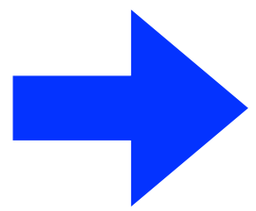
Motivation

- Weak scale unstable under quantum corrections, can be stabilized with new physics at TeV scale

- Negative LHC searches leave existing models tuned at sub-percent level: **"Little Hierarchy Problem"**

- Can be addressed by taking Higgs as PGB

  cancel largest one-loop corrections with new top/ gauge partners ~500 GeV

  weak scale stable up to multi-TeV

Solving the Little Hierarchy problem

" Little Higgs "

Arkani-Hamed, Cohen, Georgi '01

Higgs is PGB of explicitly realized global symmetry that is collectively broken:

top partners colored

" Twin Higgs "

Chacko, Goh, Harnik '06

Higgs is PGB of accidental global symmetry from explicit Z2 symmetry

top partners uncolored

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Need UV completion that addresses Big Hierarchy

Composite Higgs

Barbieri, Greco, Rattazzi, Wulzer '15

Low, Tesi, Wang '15

Supersymmetry

Chang, Hall, Weiner '06

Falkowski, Pokorski, Schmaltz '06

Craig, Howe '13

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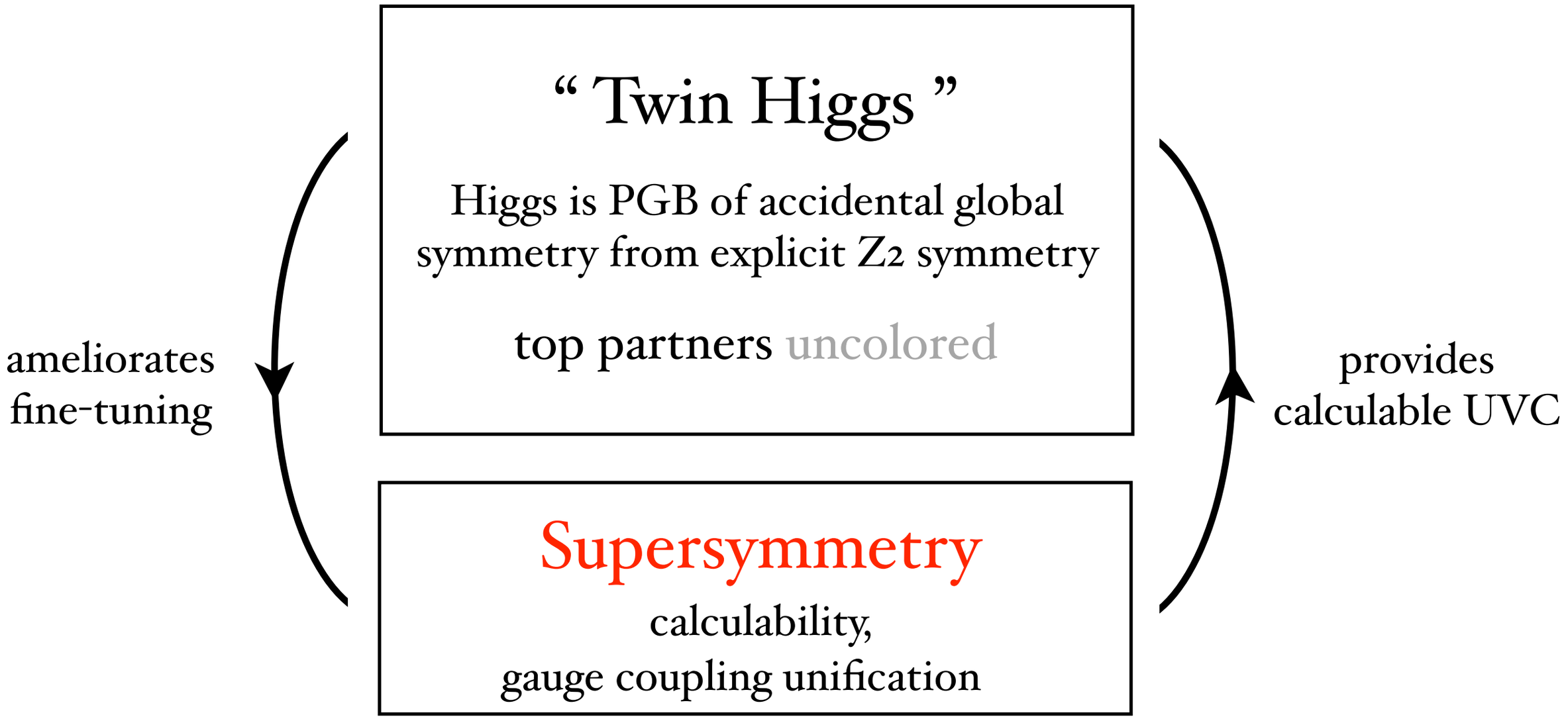
calculability, gauge coupling unification...

Twin SUSY



Only few existing models (tuning 1-2 %), still much room for model-building. **Explore general structure and identify new promising directions** (tuning 10 - 20 % !?)

Twin Higgs: **Setup**

Double SM gauge fields, Higgs and tops

$$
\begin{array}{rcccc}
G_{\rm SM} & \longrightarrow & G^A_{\rm SM} & \times & G^B_{\rm SM} \\
H, Q_3, U_3 & \longrightarrow & H_A, \underbrace{Q_{3A}, U_{3A}}_{\text{visible sector}} & + & H_B, \underbrace{Q_{3B}, U_{3B}}_{\text{“dark” sector: neutral under SM!}}
\end{array}
$$

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

Minimal (“fraternal”) Twin Higgs; double only fields most relevant for naturalness + add what is needed for anomaly cancellation

Twin Higgs: **Potential**

Classify Higgs potential according to symmetry

$$V_H(H_A, H_B) = \underbrace{V_H^{U_4}}_{\substack{\text{depends} \\ \text{only on}}} + \underbrace{V_H^{\psi_4, Z_2}}_{\substack{\text{respects} \\ H_A \leftrightarrow H_B}} + \underbrace{V_H^{\psi_4, \not{Z}_2}}_{\substack{\text{respects only} \\ \text{gauge symmetry}}}$$

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

U_4 part dominant, negative mass term

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

Dark Higgs gets large U_4 breaking vev

$$H_B^\dagger H_B = f^2 - H_A^\dagger H_A$$

7 GB - 3 eaten by dark gauge bosons = SM Higgs $\approx H_A$

Twin Higgs: **Stability**

Radiative corrections mainly from top sector

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

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

Twin Higgs: **Stability**

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Impose Z_2 invariance

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

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

Twin Higgs: **Stability**

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

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Impose Z_2 invariance

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

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

U_4 invariant! Just large correction to f $\delta f \sim \Lambda/4\pi$

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

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

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

N.B.: On bilinear level Z2 invariance automatically implies U4 invariance

Twin Higgs: **EWSB**

$$V_H(H_A, H_B) = \underbrace{V_H^{U_4}}_{\lambda\left(|H_A|^2 + |H_B|^2 - f^2\right)} + \underbrace{V_H^{\psi_4, Z_2}}_{\kappa\left[|H_A|^4 + |H_B|^4\right]} + \underbrace{V_H^{\psi_4, \not{Z}_2}}_{\rho|H_A|^4 + \sigma f^2 |H_A|^2}$$

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

mainly tree

hard Z2 breaking:
must be small

Match to SM Higgs potential and get electroweak scale

$$v^2 \sim \left(1 - \frac{\sigma}{\kappa + \text{loop}}\right) f^2$$

need explicit Z2 breaking,
tuned to get v/f hierarchy

Twin SUSY: **Setup**

Double MSSM gauge superfields, Higgs and tops

$$H_u, H_d, Q_3, U_3 \longrightarrow \underbrace{H_{uA}, H_{dA}, Q_{3A}, U_{3A}}_{\text{visible sector}} + \underbrace{H_{uB}, H_{dB}, Q_{3B}, U_{3B}}_{\text{“dark” sector: neutral under SM!}}$$

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

$$\mathcal{H}_{u,d} = \begin{pmatrix} H_A \\ H_B \end{pmatrix}_{u,d}$$

$$W \supset \lambda S \mathcal{H}_u \mathcal{H}_d$$

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

$$\boxed{V^{U_4} = m_u^2 |\mathcal{H}_u|^2 + m_d^2 |\mathcal{H}_d|^2 - b\,(\mathcal{H}_u \mathcal{H}_d + \text{h.c.}) + \lambda^2 |\mathcal{H}_u \mathcal{H}_d|^2}$$

Induce dark higgs vevs: $\quad f^2 = \dfrac{m_A^2 - m_u^2 - m_d^2}{\lambda^2} \qquad \tan^2\beta = \dfrac{m_d^2}{m_u^2}$

Twin SUSY: **Potential**

Classify Higgs potential according to symmetry

$$V_H(H_{uA}, H_{dA}, H_{uB}, H_{dB}) = \underbrace{V_H^{U_4}}_{\text{generates f}} + \underbrace{V_H^{\Psi_4, Z_2} + V_H^{\Psi_4, \not{Z}_2}}_{\text{generates v}}$$

Huge freedom, need systematic approach:

- List U4 breaking operators, divide in Z2 even/odd
- Use PGB approximation: keep only lightest CP-even Higgs
- Match to SM Higgs potential: just 2 parameters
- Check numerically

Twin SUSY: **EWSB**

Match all operators on 2 eff. parameters in PGB approx

$$V^{\psi}{}_4 = f^4 \left[\left(\cos^4 + \sin^4\right) \underbrace{A_4}_{\text{Z2 even: quartic}} + \left(\cos^2 - \sin^2\right) \underbrace{\Delta}_{\text{Z2 odd}} \right] \qquad \sin \equiv \sin\left(\frac{h}{\sqrt{2}f}\right)$$

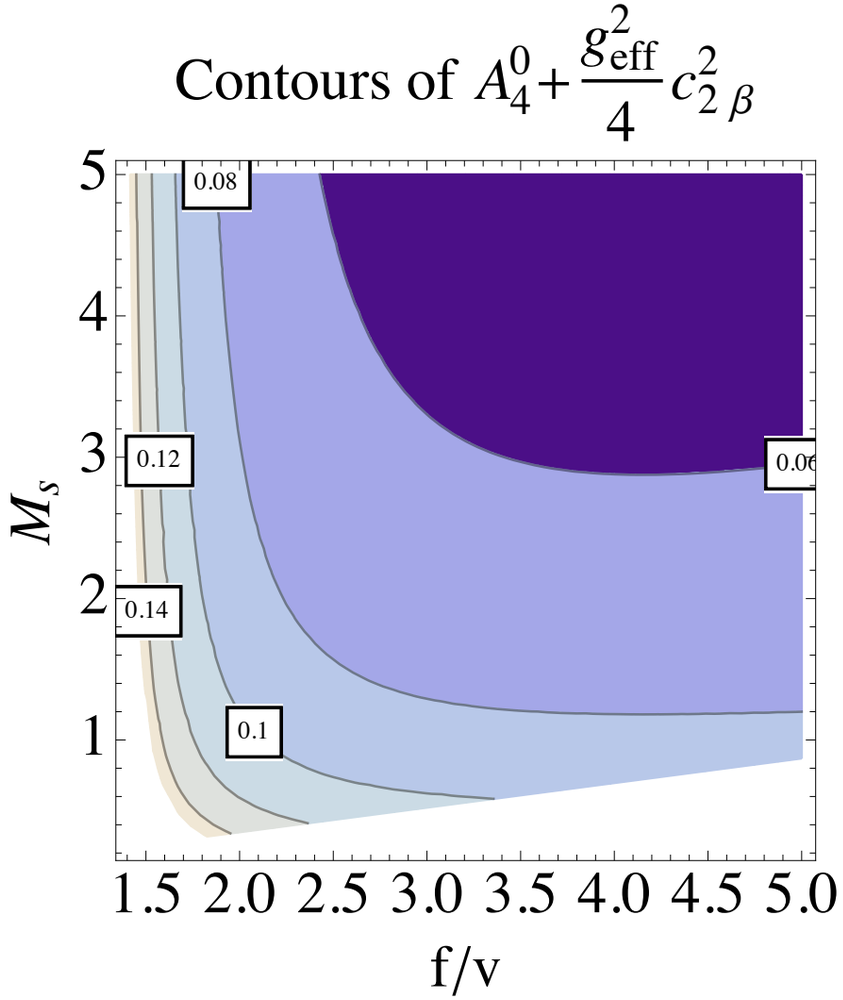
$$\frac{v^2}{f^2} = \frac{1}{2}\left(\frac{A_4 + \Delta}{A_4}\right) \qquad m_h^2 = 8v^2\left(1 - \frac{v^2}{f^2}\right) A_4$$

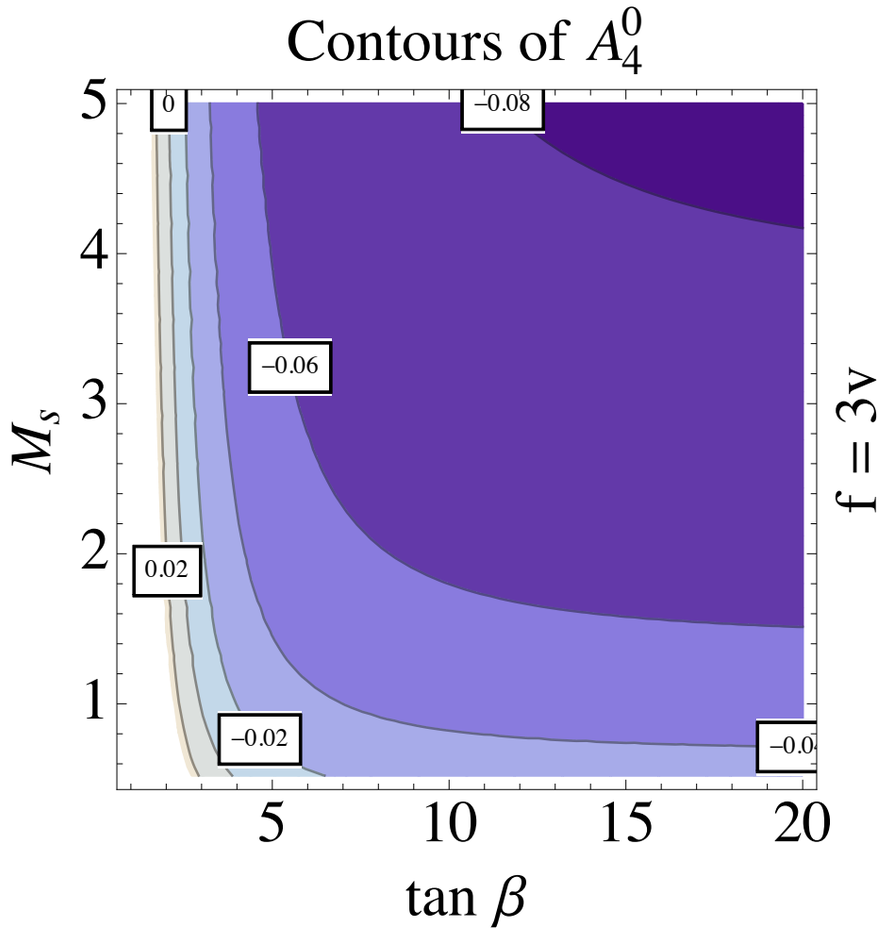
receive irreducible contributions from top/stop loops & tree-level D-term + model-dependent

$$A_4 = A_4^{\mathrm{D-term}}(t_\beta) + A_4^{1-\mathrm{loop}}(M_S, f) + A_4^0$$

$$\Delta = \underbrace{\Delta^{1-\mathrm{loop}}(M_S, f)}_{\text{small}} + \Delta^0 \approx -0.11$$

Twin SUSY: **EWSB**





Upper bound on A4 from Higgs mass: grows with MS (stop contribution) and tanb (D-term)

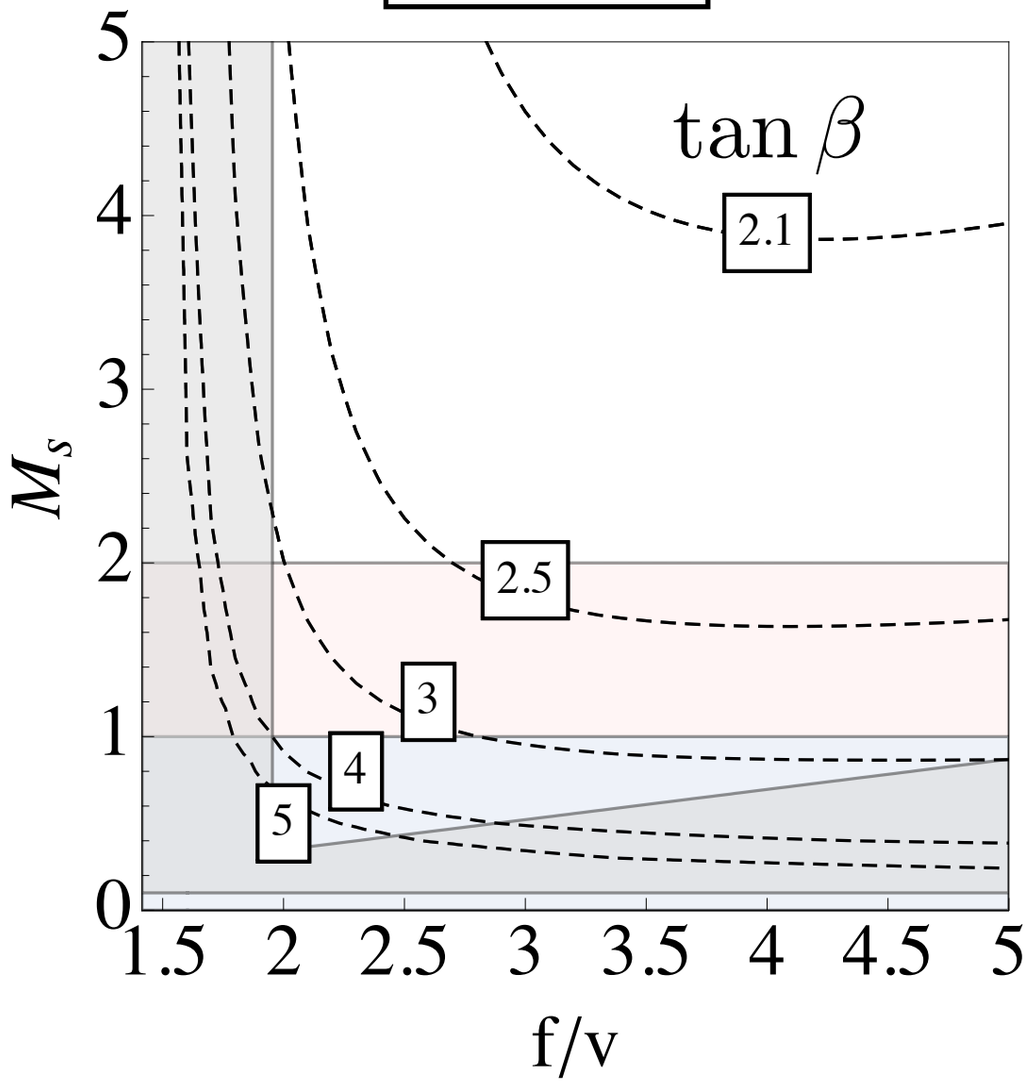
Prefers **negative** A_4^0 but difficult to generate

Twin SUSY: **Parameter Space**

Two examples for Z2 breaking terms

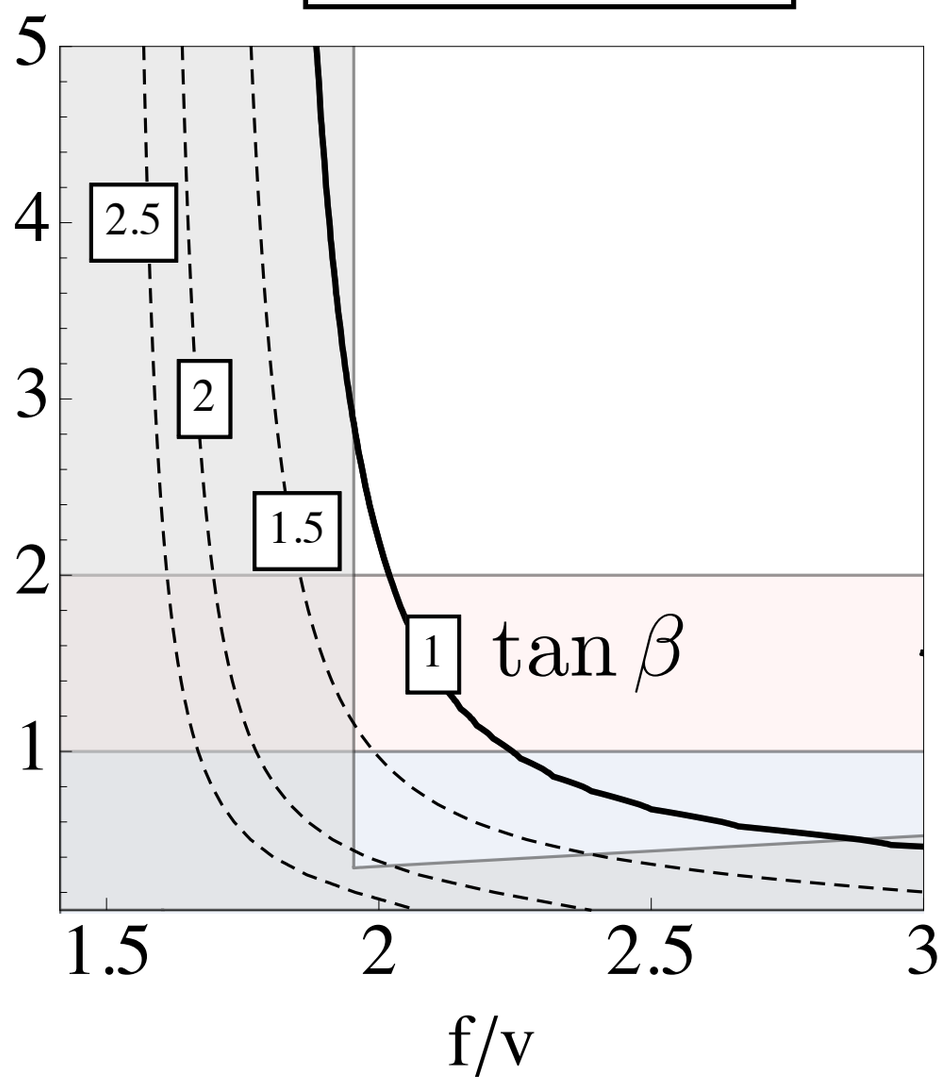
$$V_{\rm soft}^{\not\psi_4,\not Z_2} = \Delta m_{H_u}^2 |H_{uA}|^2$$

$$A_4^0 = 0$$



$$V_{\rm hard}^{\not\psi_4,\not Z_2} = \lambda_A^2 |H_{uA} H_{dA}|^2$$

$$A_4^0 = \lambda_A^2/2$$



Twin SUSY: **Fine-tuning**

Two sources of tuning

$$\underbrace{f/M_S}$$

U4 , similar NMSSM tuning v → f

$$\Delta_f \sim \frac{\delta m_{H_u}^2}{2\lambda^2 f^2 c_\beta^2}$$

$$\underbrace{v/f}$$

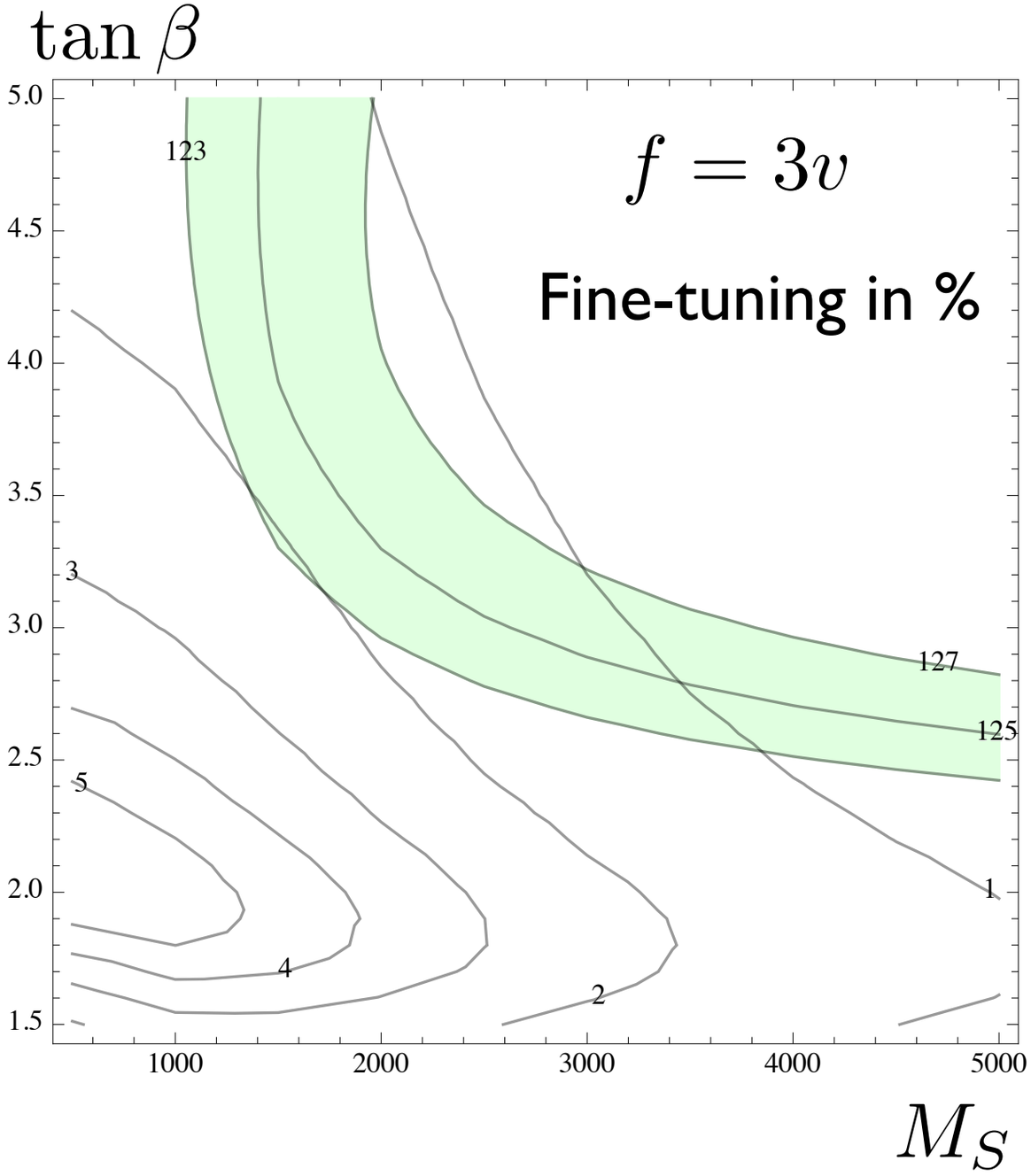
U4 breaking, model-dependent

$$\Delta_v^{\rm soft} \sim \frac{f^2}{2v^2} \Big/ \Delta_v^{\rm hard} \sim 1$$

Soft breaking needs tuning to get v/f hierarchy: total tuning like NMSSM

Hard breaking gets naturally v/f hierarchy: total tuning better by factor 5-10 (PGB), but restricted parameter space

Twin SUSY: **Numerics**



in progress...

found points with

$$\tan\beta \approx 1.3$$
$$f \approx 4v$$
$$M_S \approx 1000\,\mathrm{GeV}$$
$$m_h \approx 125\,\mathrm{GeV}$$

tuning $\approx (10-20)\%$

preliminary!

Soft Z2 breaking

Hard Z2 breaking

Summary

- Twin Higgs models can stabilize weak scale up to 5-10 TeV without colored top partners

- SUSY provides UV completion with calculable observables: Twin SUSY

- Many possibilities for Z_2 breaking, only few have been explored: systematic approach

- Particularly interesting are hard Z_2 breaking models, allow for natural v/f hierarchy

Backup

Twin SUSY: **Stability**

Radiative corrections from stop/top sector

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

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

$$\Delta V_{top} = -\frac{3}{16\pi^2}\left[y_t^2\left(|H_A|^2 + |H_B|^2\right)\Lambda^2 + \log\ldots\right]$$

$$\Delta V_{stop} = +\frac{3}{16\pi^2}\left[y_t^2\left(|H_A|^2 + |H_B|^2\right)\Lambda^2 + \log\ldots\right]$$

SUSY

twin

$$\Delta V = \frac{3}{16\pi^2}\left[-2y_t^2 M_S^2 |\mathcal{H}_u|^2 \log\frac{\Lambda_{mess}^2}{M_S^2} + y_t^4\left(|H_{uA}|^4 \log\frac{M_S^2}{m_{tA}^2} + |H_{uB}|^4 \log\frac{M_S^2}{m_{tB}^2}\right)\right]$$

usual stop correction to $m_{H_u}^2$: $\delta f \sim M_S/4\pi$

generates PGB quartic and mass term : $\delta m_h \sim f/4\pi$

Twin Higgs Phenomenology

- Dark sector couples only through Higgs portal

  mixing angle v/f

- Primary signal from SM Higgs couplings

$$f/v \gtrsim 2.2$$

- Many DM candidates in Dark Sector

$$\tau_B, W_B, \ldots$$