Twin SUSY Model Building

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work in progress with
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A First Glance Beyond the Energy Frontier
ICTP, September 6, 2016

Motivation

" Twin Higgs"

Chacko, Goh, Harnik '06

is simple realization of "Neutral Naturalness"

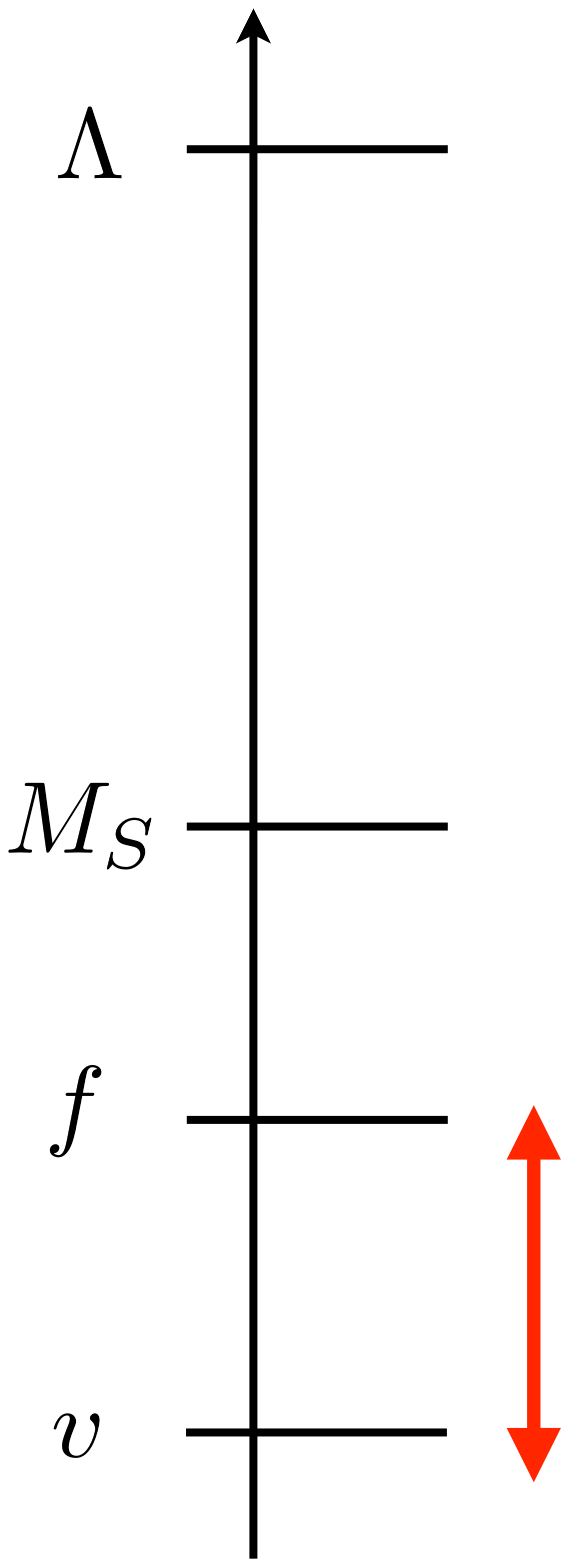
Higgs is PGB of accidental global symmetry from explicit Z_2 symmetry

top partners uncolored

Z_2 breaking introduces some model dependence

→ Explore parameter space of Twin Higgs and its SUSY UV completions

Outline



A fresh look to the Twin Higgs

soft vs. **hard** Z_2 breaking

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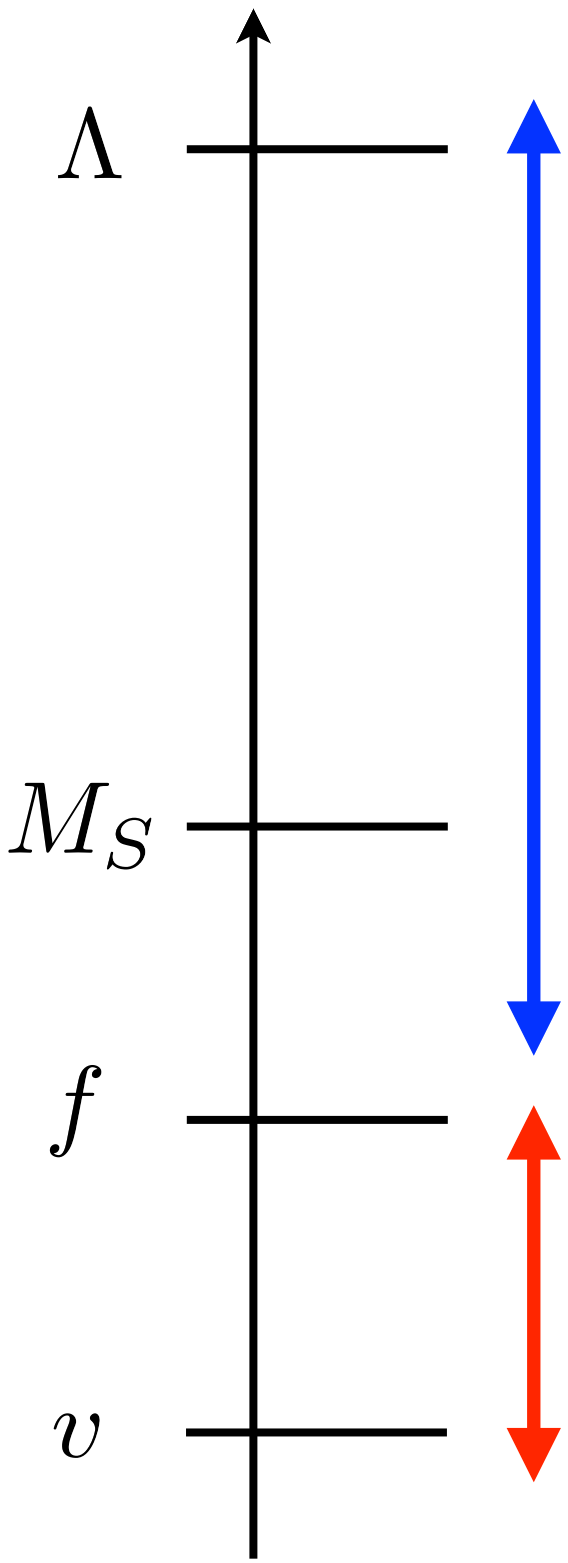

SUSY UV Completions

hard Z_2 breaking **vs. m_h**

A fresh look to the Twin Higgs

soft vs. **hard** Z_2 breaking

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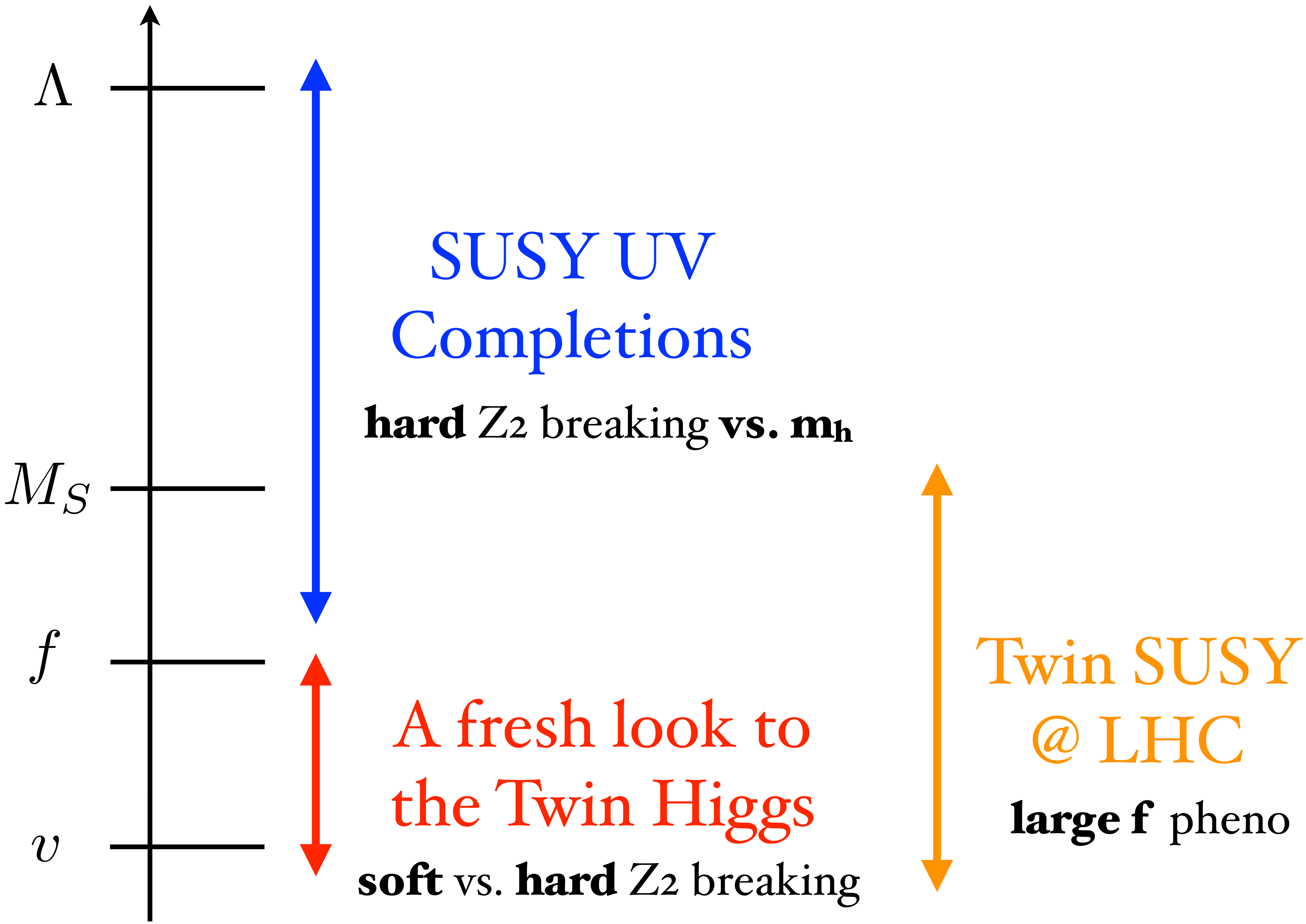

Λ
M_S
f
v
SUSY UV Completions
hard Z2 breaking **vs. m$_h$**
A fresh look to the Twin Higgs
soft vs. **hard** Z2 breaking
Twin SUSY @ LHC
large f pheno

A fresh look to the Twin Higgs

Twin Higgs Setup

Double SM gauge fields, Higgs and tops

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

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

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

Twin Higgs Setup

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

$$H, Q_3, U_3 \rightarrow H_A, \underbrace{Q_{3A}}_{\text{visible sector}}, U_{3A} + H_B, \underbrace{Q_{3B}}_{\text{"dark" sector: neutral under SM}}, U_{3B}$$

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

Here we focus on fine-tuning: just Higgs, gauge and tops doubled

- Z_2 involves the full SM — 0509242 Barbieri, Hall & Gregoire
- Minimal ("fraternal") Twin Higgs — 1501.05310 Craig, Katz, Strassler & Sundrum

Higgs Potential

$$V = \lambda(|H_A|^2 + |H_B|^2 - f^2)^2 + \kappa(|H_A|^4 + |H_B|^4) + \tilde{\mu}^2|H_A|^2 + \rho|H_A|^4$$

Higgs Potential

$$V = \underbrace{\lambda(|H_A|^2 + |H_B|^2 - f^2)^2}_{V_{U_4}} + \kappa(|H_A|^4 + |H_B|^4) + \tilde{\mu}^2|H_A|^2 + \rho|H_A|^4$$

respects $U(4)$

for $\lambda > 0$, $f^2 > 0$
spontaneously broken

7 GB - 3 eaten = SM Higgs

radial mode gets mass

$$m_H^2 \sim \lambda f^2$$

Higgs Potential

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V_{U_4}	$V_{\not{U}_4, Z_2}$
respects $U(4)$	respects $H_A \leftrightarrow H_B$
for $\lambda > 0$, $f^2 > 0$ spontaneously broken	for $\kappa > 0$ Z_2 unbroken, $v_A = v_B$
7 GB - 3 eaten = SM Higgs	maximal mixing (excluded)
radial mode gets mass $m_H^2 \sim \lambda f^2$	PGB gets mass $m_h^2 \sim \kappa f^2 \ll m_H^2$ $\uparrow$ $\kappa \ll \lambda$

Higgs Potential

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$\lambda(|H_A|^2 + |H_B|^2 - f^2)^2$: V_{U_4}

respects $U(4)$

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$m_H^2 \sim \lambda f^2$

$\kappa(|H_A|^4 + |H_B|^4)$: $V_{\not{U}_4, Z_2}$

respects $H_A \leftrightarrow H_B$

for $\kappa > 0$
Z_2 unbroken, $v_A = v_B$

maximal mixing
(excluded)

PGB gets mass

$m_h^2 \sim \kappa f^2 \ll m_H^2$

$\uparrow$ $\kappa \ll \lambda$

$\tilde{\mu}^2|H_A|^2 + \rho|H_A|^4$: $V_{\not{U}_4, \not{Z}_2}$

$\tilde{\mu}^2$ **soft** breaking
ρ **hard** breaking

allows for hierarchy
$v \equiv v_A < v_B \approx f$

controls mixing
$s_\theta \approx v/f$

Higgs couplings give
$f/v > 2.3$

EWSB

PGB approximation $\kappa \ll \lambda$

$$V(h) = -\frac{f^2}{2}\left(2\kappa - \sigma\right) h^2 + \frac{1}{12}\left(8\kappa + 3\rho - \sigma\right) h^4$$

$\sigma \equiv \tilde{\mu}^2/f^2$

$$\frac{v^2}{f^2} = \frac{1}{2}\left(\frac{\kappa - \frac{\sigma}{2}}{\kappa + \frac{\rho}{2}}\right)$$

$$m_h^2 \approx 4f^2\left(\kappa - \frac{\sigma}{2}\right) \approx 8v^2\left(\kappa + \frac{\rho}{2}\right)$$

Soft Z2 Breaking

$\rho \ll \sigma$

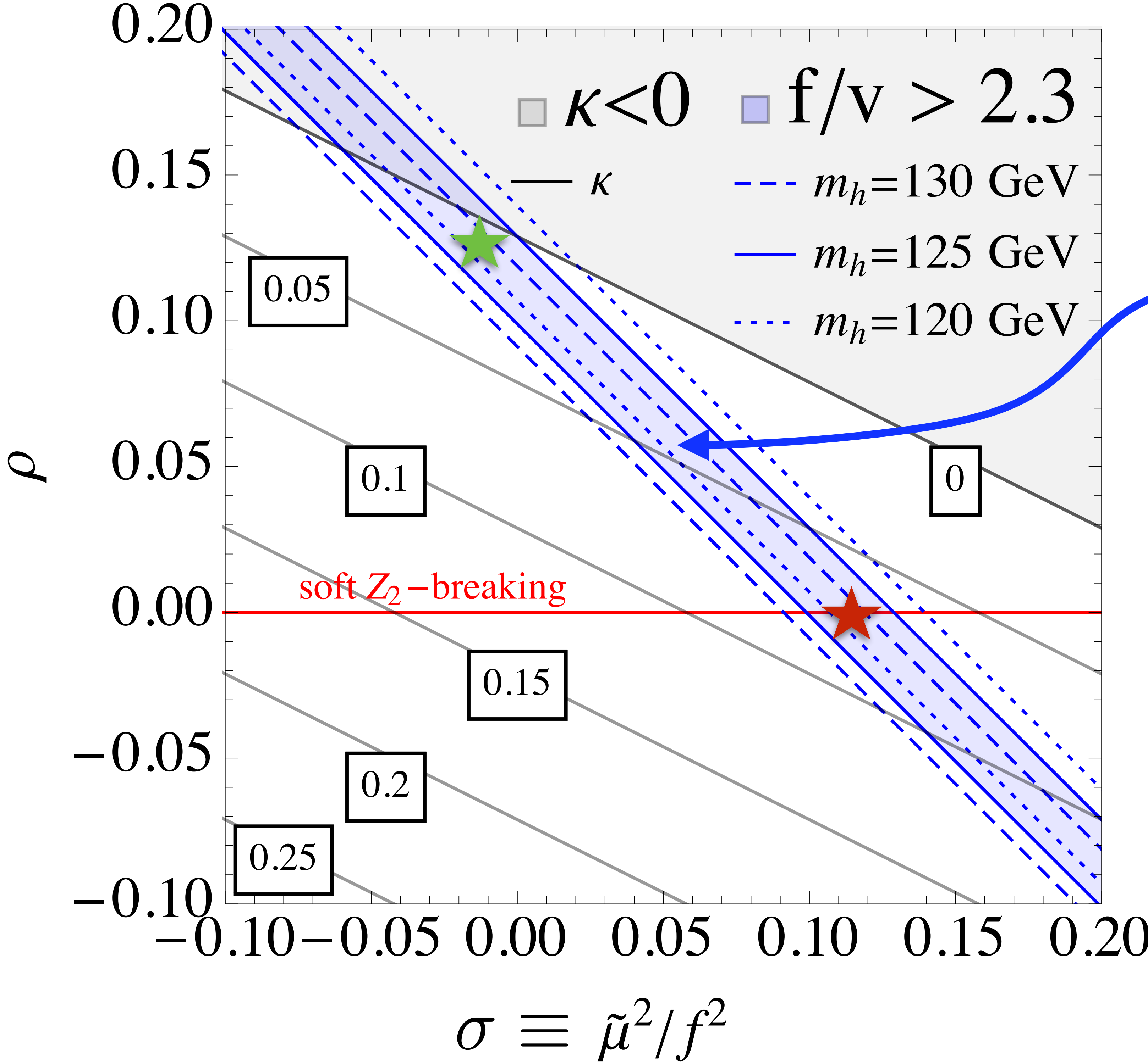
- need tuning for $v \ll f$
- light Higgs $m_h^2 \approx 8\kappa v^2$.

Hard Z2 Breaking

$\rho \gg \sigma$

- naturally $v \ll f$ for $\rho \gg \kappa$
- heavy Higgs $m_h^2 \approx 4\kappa f^2$

EWSB

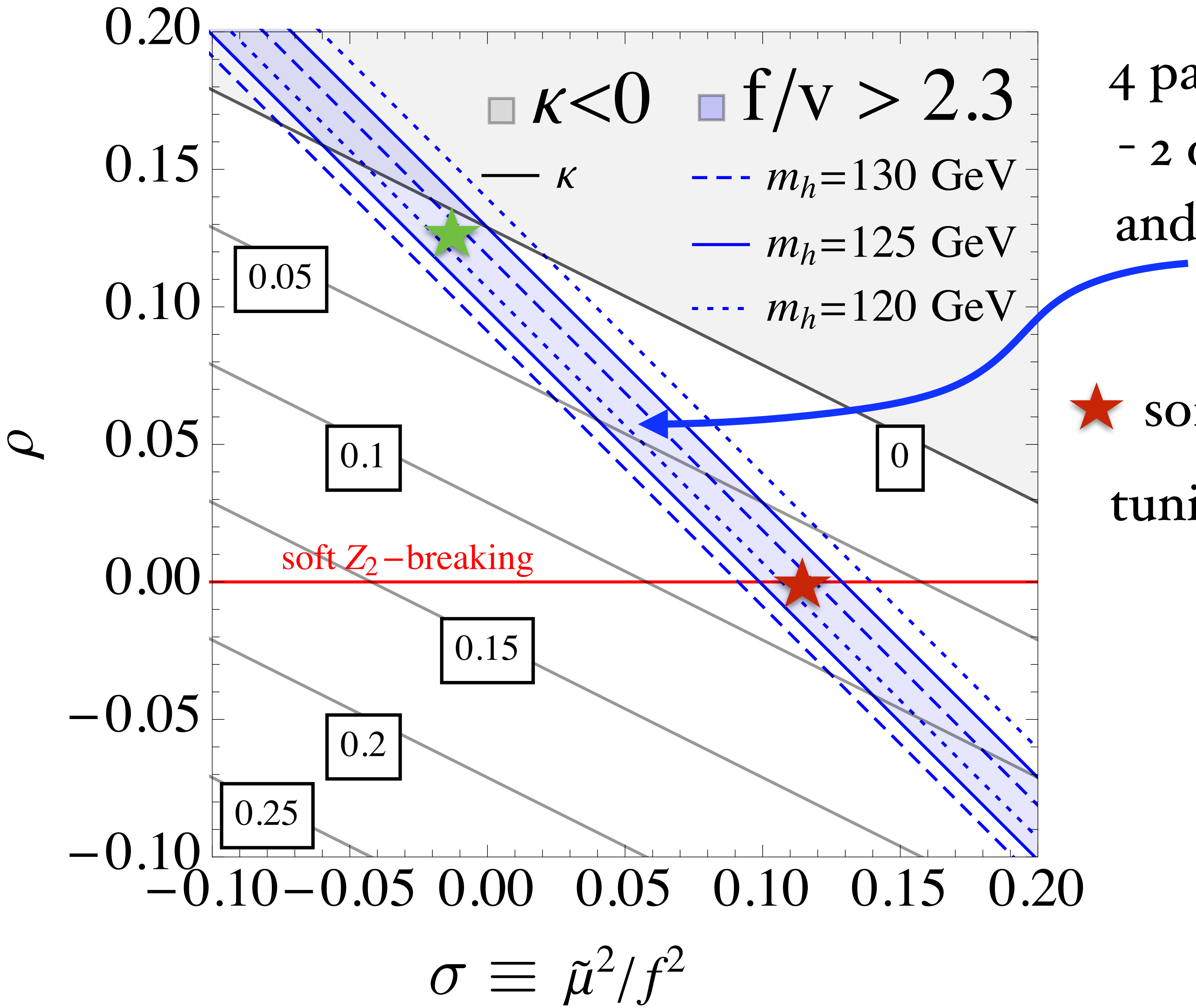


4 parameters $\{f, \kappa, \sigma, \rho\}$

- 2 observables $\{v, m_h\}$

and constraint $f/v > 2.3$

EWSB



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tuning $\sigma \approx 2\kappa$ to get $f/v > 2.3$

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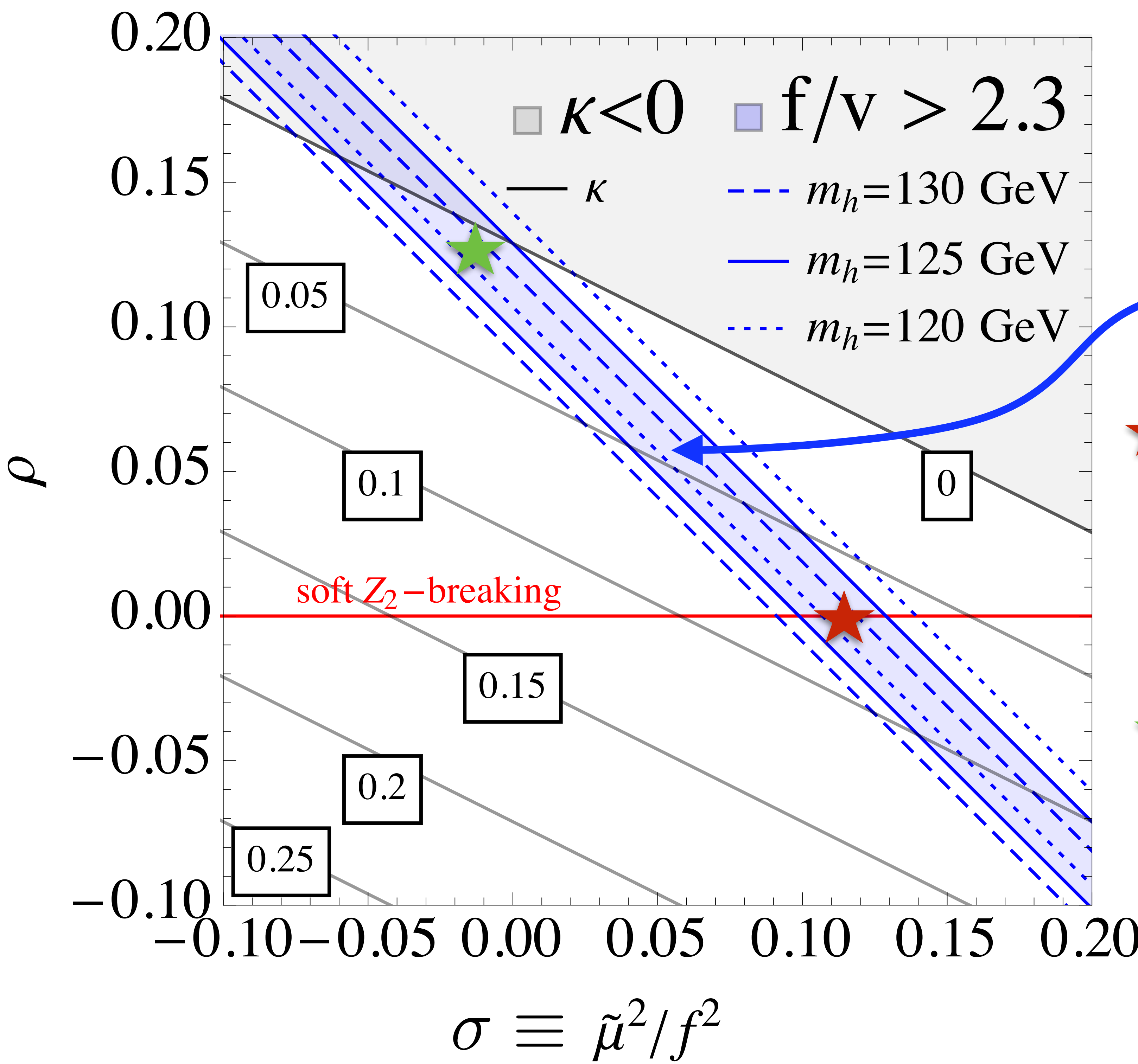

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★ hard-breaking: $\rho \gg \sigma$

tuning $\kappa \ll \rho$ to get m_h

Include Quantum Corrections

"freezing logs" we can match to the tree-level potential

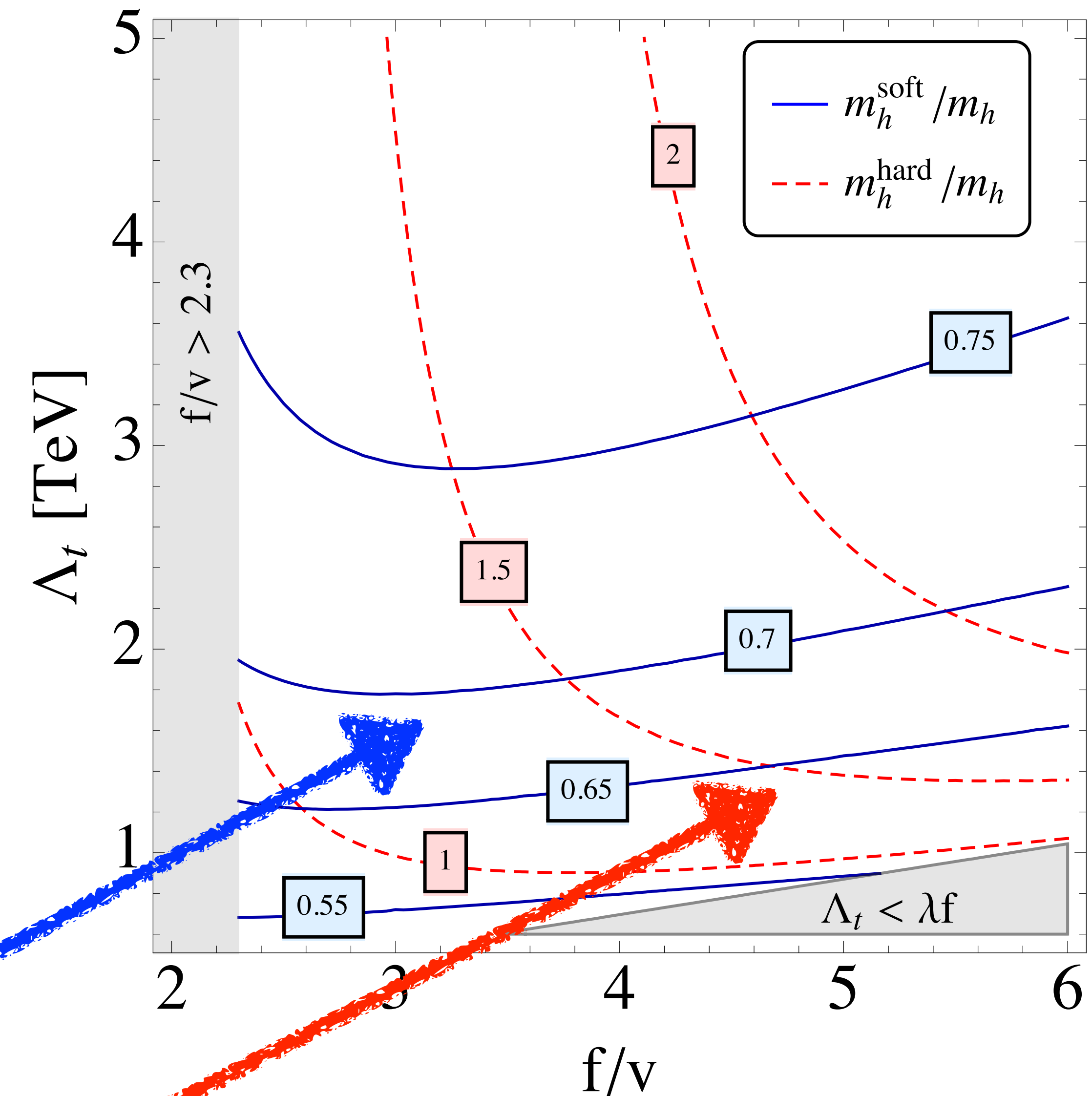
$$\kappa = \kappa_0 + \kappa_{\rm top} + \kappa_{\rm hard} \approx \kappa_0 + \frac{3y_t^4}{16\pi^2}\log\frac{\Lambda_t^2}{y_t^2 f^2}$$

$$\tilde{\mu}^2 = \tilde{\mu}_0^2 + \tilde{\mu}_{\rm top}^2 + \tilde{\mu}_{\rm hard}^2 \approx \tilde{\mu}_0^2 + \frac{\rho}{8\pi^2}\Lambda_\rho^2$$

$$\rho = \rho_0 + \rho_{\rm top} + \rho_{\rm hard} \approx \rho_0$$

contributions from top sector

contributions from higgs sector with hard-breaking



Soft Breaking

top makes ~70% of Higgs mass

(pure) Hard Breaking

top makes ~150% of Higgs mass

Soft vs. Hard Breaking

Soft $[\rho_0 = 0]$

$$m_h^2 \approx 8v^2\kappa = 8v^2\left(\kappa_0^{\text{soft}} + \kappa_{\text{top}}\right)$$

makes ~70%

$$\Delta_{v/f} \approx \frac{f^2}{2v^2}$$

Need $\kappa_0^{\text{soft}} > 0$ for $m_h = 125$ GeV

Hard $[\tilde{\mu}_0^2 = 0]$

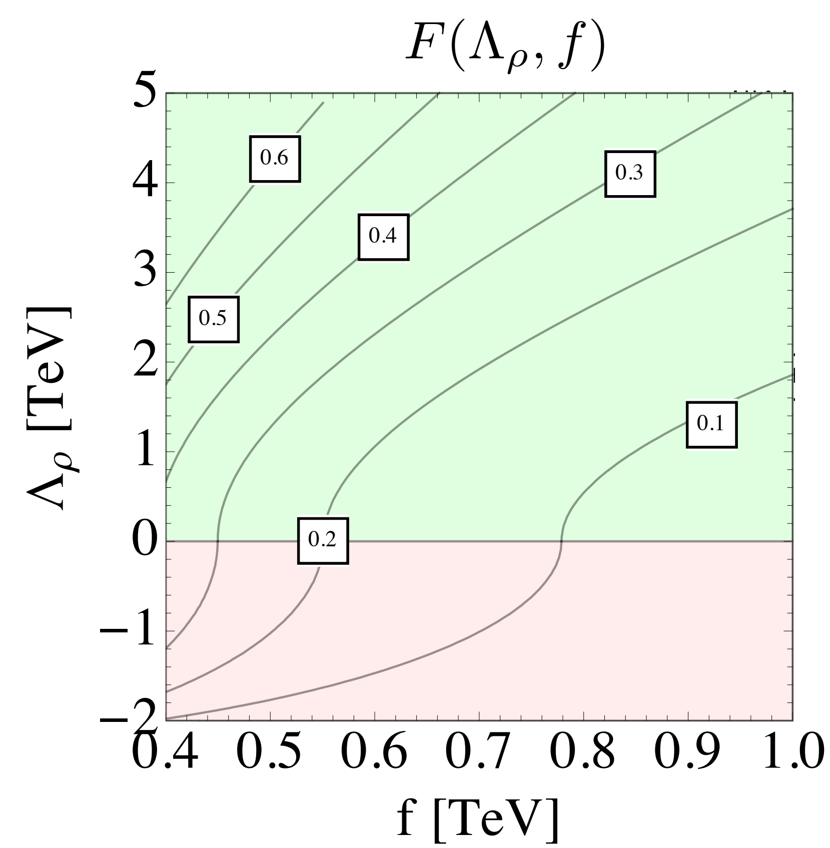
$$m_h^2 \approx \frac{8v^2}{F(\Lambda_\rho, f)}\kappa = \frac{8v^2}{F(\Lambda_\rho, f)}\left(\kappa_0^{\text{hard}} + \kappa_{\text{top}}\right)$$

$$\Delta_{v/f} \approx \frac{f^2}{2v^2} F(\Lambda_\rho, f)$$

Need $\kappa_0^{\text{hard}} \lesssim 0$ for $m_h = 125$ GeV

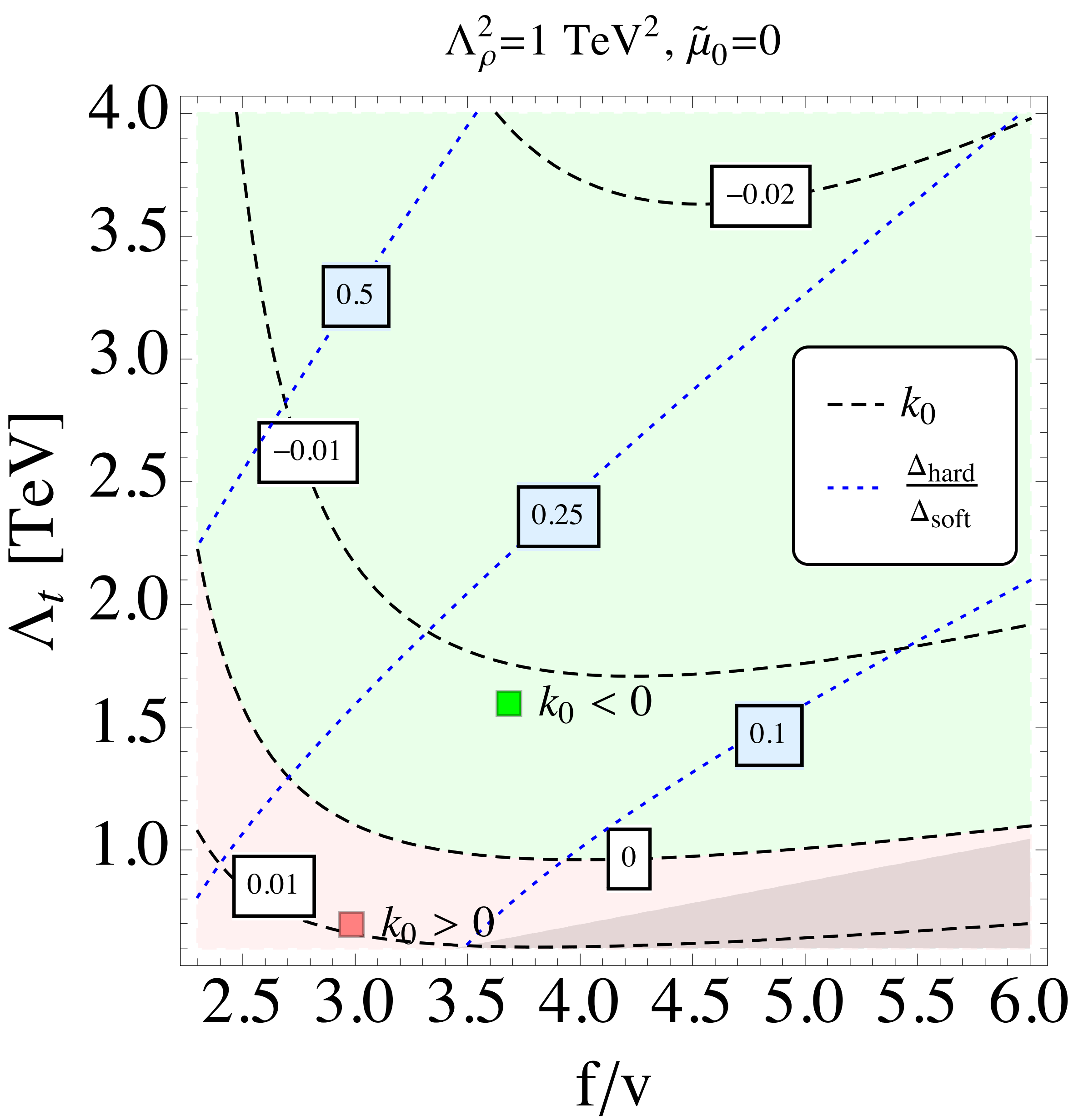
Gain in fine-tuning corresponds to enhancement of Higgs mass

$$F(\Lambda_\rho, f) = \frac{\Lambda_\rho^2 + 16\pi^2 v^2}{\Lambda_\rho^2 + 8\pi^2 f^2}$$



Making hard breaking viable

$\kappa_0^{\text{hard}} \lesssim 0$

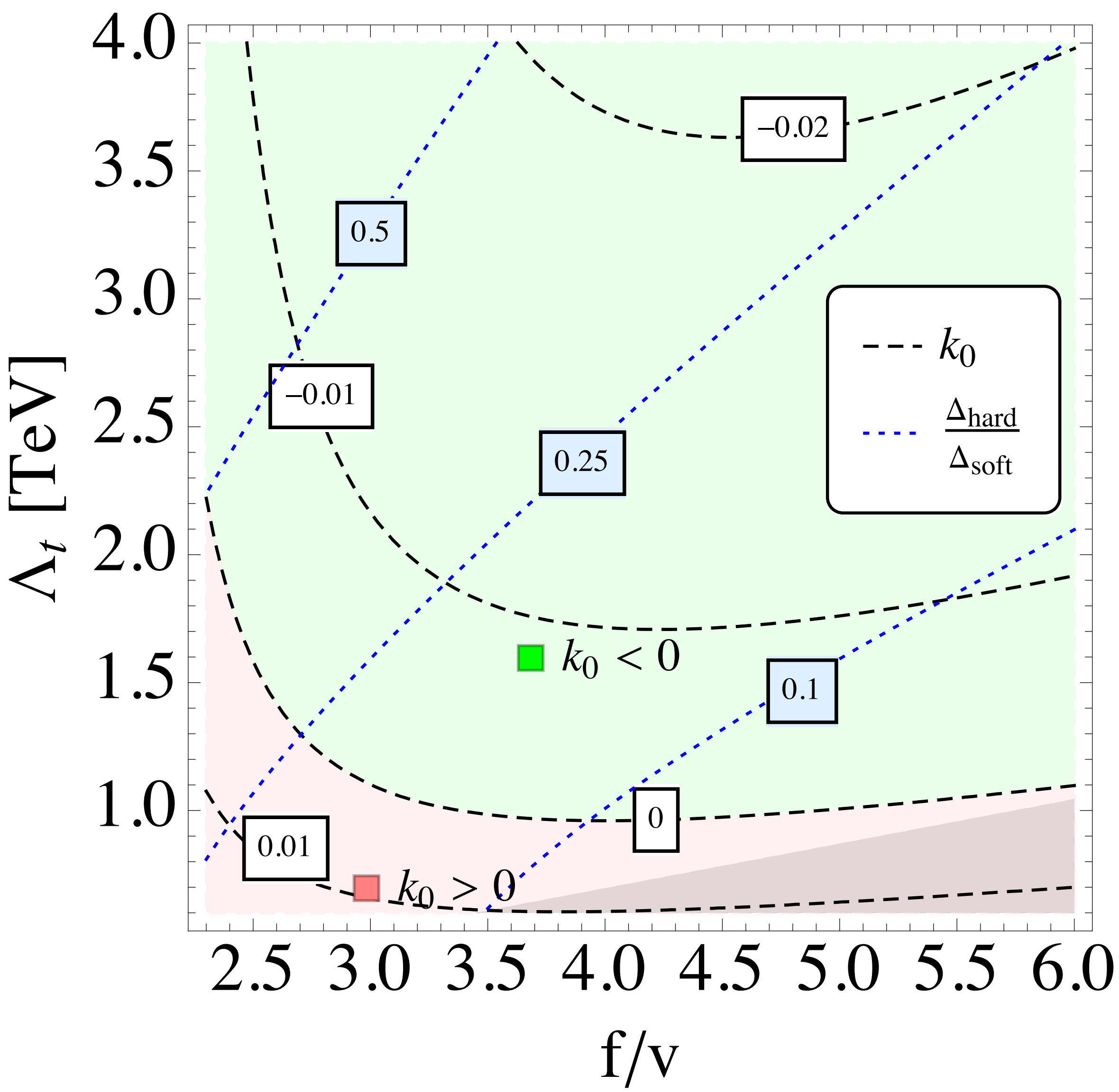


Sign of κ_0 is crucial!

Making hard breaking viable

$\kappa_0^{\text{hard}} \lesssim 0$

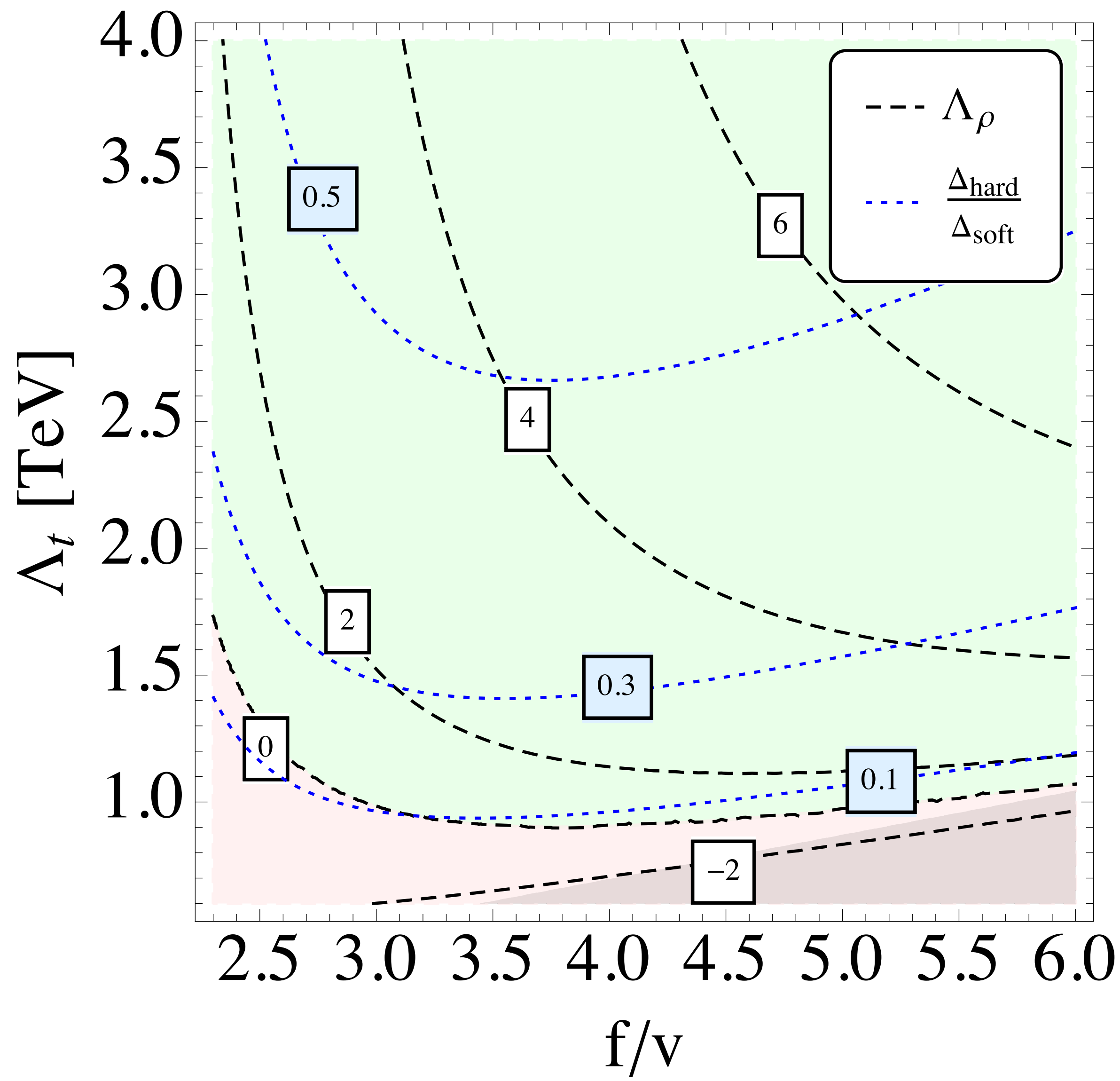
Λ_ρ^2=1 TeV^2, $\tilde{\mu}_0$=0



Sign of κ_0 is crucial!

Play with UV threshold Λ_ρ

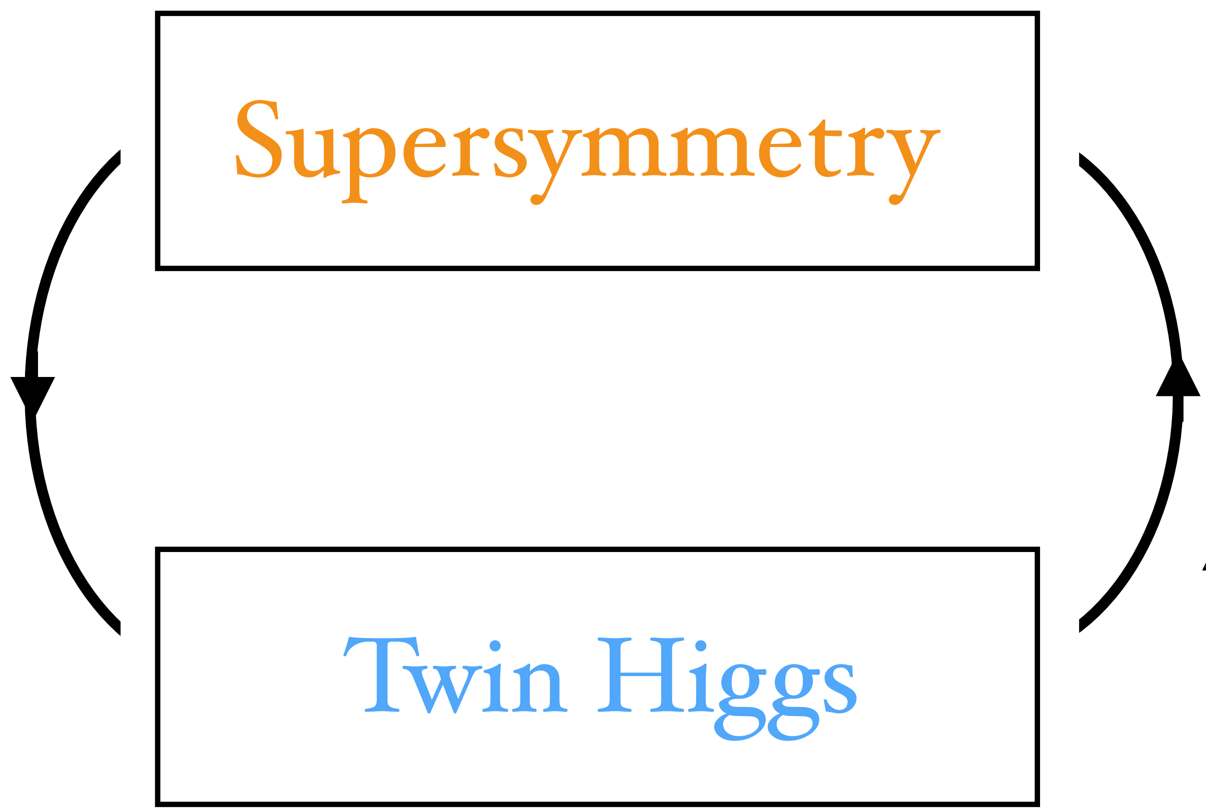
$\kappa_0 = 0, \tilde{\mu}_0 = 0$



Sign of Λ_ρ^2 is crucial!

SUSY UV Completions

Twin SUSY



provides calculable UVC

$$\Lambda_{t,\rho} \sim M_S$$

ameliorates fine-tuning

$$\Delta_{\mathrm{MSSM}} = \frac{3y_t^2 M_S^2}{2\pi^2 m_h^2} \log \frac{\Lambda}{M_S} \sim 100$$

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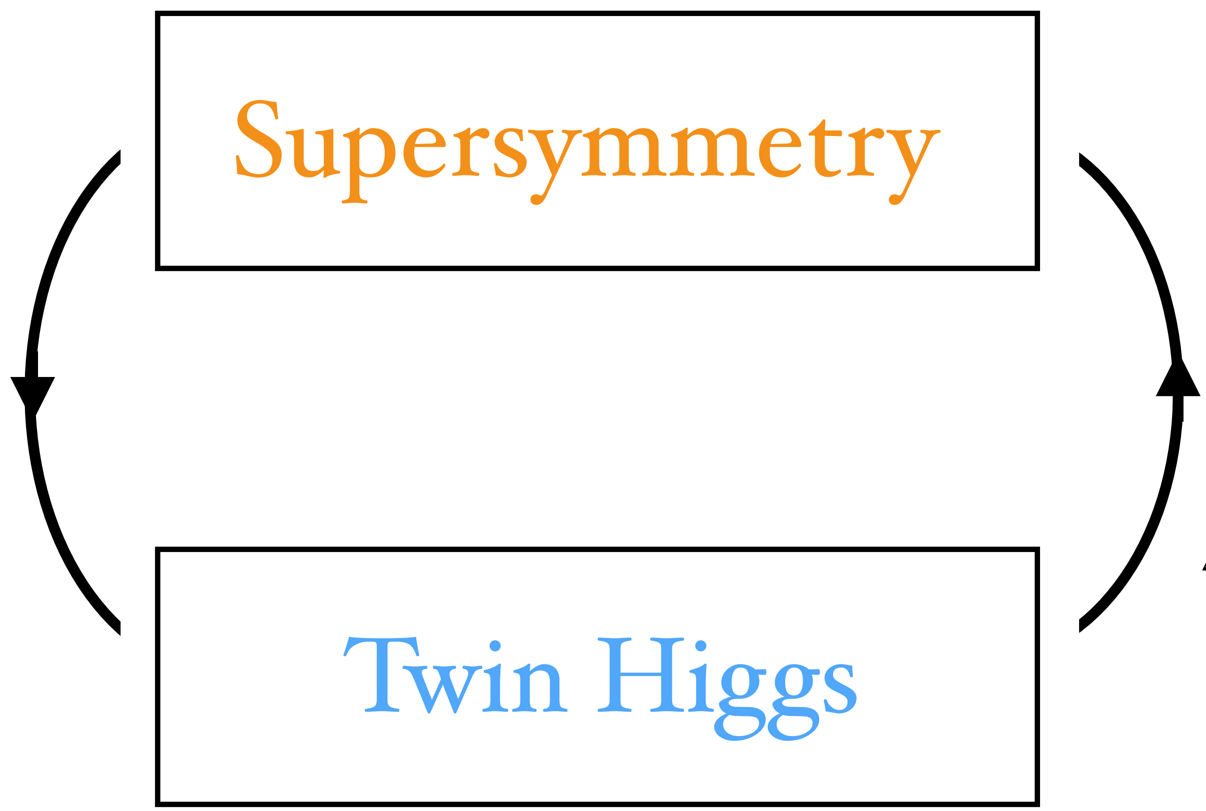

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Only few existing models (tuning 1-2 %)

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

Explore Twin SUSY with *Hard Breaking* (tuning 5-10 % !?)

Twin SUSY Matching

$$V = \underbrace{\lambda(|H_A|^2 + |H_B|^2 - f^2)^2}_{V_{U_4}} + \underbrace{\kappa(|H_A|^4 + |H_B|^4)}_{V_{\not{U}_4, Z_2}} + \underbrace{\tilde{\mu}^2|H_A|^2 + \rho|H_A|^4}_{V_{\not{U}_4, \not{Z}_2}}$$

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★ quartic from non-dec. F-term

$$W = \lambda_S S \mathcal{H}_u \mathcal{H}_d \xrightarrow[m_S \gg M_S]{} \lambda \approx \frac{\lambda_S^2}{4} s_{2\beta}^2$$

★ mass from soft Higgs masses

$$f_0^2 \approx \frac{2b\, t_\beta - m_d^2 - t_\beta^2 m_u^2}{2\lambda_S^2 s_\beta^2}$$

f tuning calculable

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★ D-term contribution

$$\kappa_0 = \frac{g_{\text{eff}}^2}{8} c_{2\beta}^2$$

★ top/stop contribution

$$\kappa_{\text{top}} = \frac{3y_t^4 s_\beta^4}{16\pi^2} \log \frac{M_S^2}{y_t^2 s_\beta^2 f^2}$$

κ large and positive: strong constraints from Higgs mass

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★ quartic from n.d. F-term

e.g.

$$W = \lambda_A S_A H_u^A H_d^A \xrightarrow[m_{S_A} \gg M_{S_A}]{} \rho = \frac{\lambda_A^2}{4} s_{2\beta}^2$$

★ mass from soft masses + loops

$$\tilde{\mu}_0^2 = \Delta m_u^2 s_\beta^2 + \Delta m_d^2 c_\beta^2$$

$$\tilde{\mu}_{\rm hard}^2 = -\frac{3\lambda_A^2}{32\pi^2} m_{S_A}^2$$

Λ_ρ^2 negative: upper bound on stop masses

Total Fine-Tuning

Two sources of tuning

$$\underbrace{f/M_S}_{\text{U4 , similar NMSSM tuning v} \to \text{f}} \quad \times \quad \underbrace{v/f}_{\text{U4 breaking, model-dependent}}$$

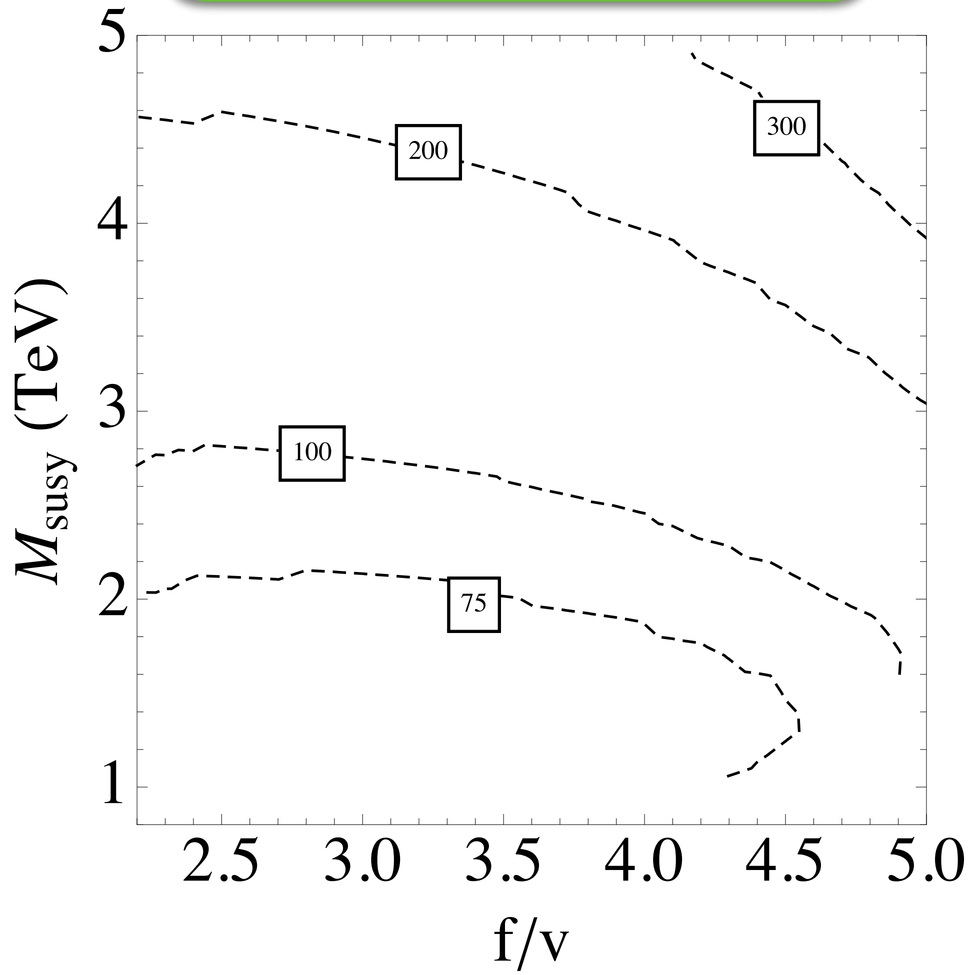
$$\frac{3y_t^2 M_S^2}{8\pi^2 \lambda_S^2 f^2 c_\beta^2} \log \frac{\Lambda}{M_S}$$

SOFT	HARD
$f^2/2v^2$	$f^2/2v^2 F(\Lambda_\rho, f)$

- Soft breaking has total tuning like NMSSM with $\lambda_{\text{NMSSM}} \to \lambda_S$ gain slightly since unrelated to Higgs mass
- Hard breaking better up to factor 10, if can fix Higgs mass depends on Z2 breaking cutoff realization

Numerical Results

Soft breaking



1% tuning

colored states decoupled from LHC

1312.1341 Craig & Howe

[prefers low f/v]

Numerical Results

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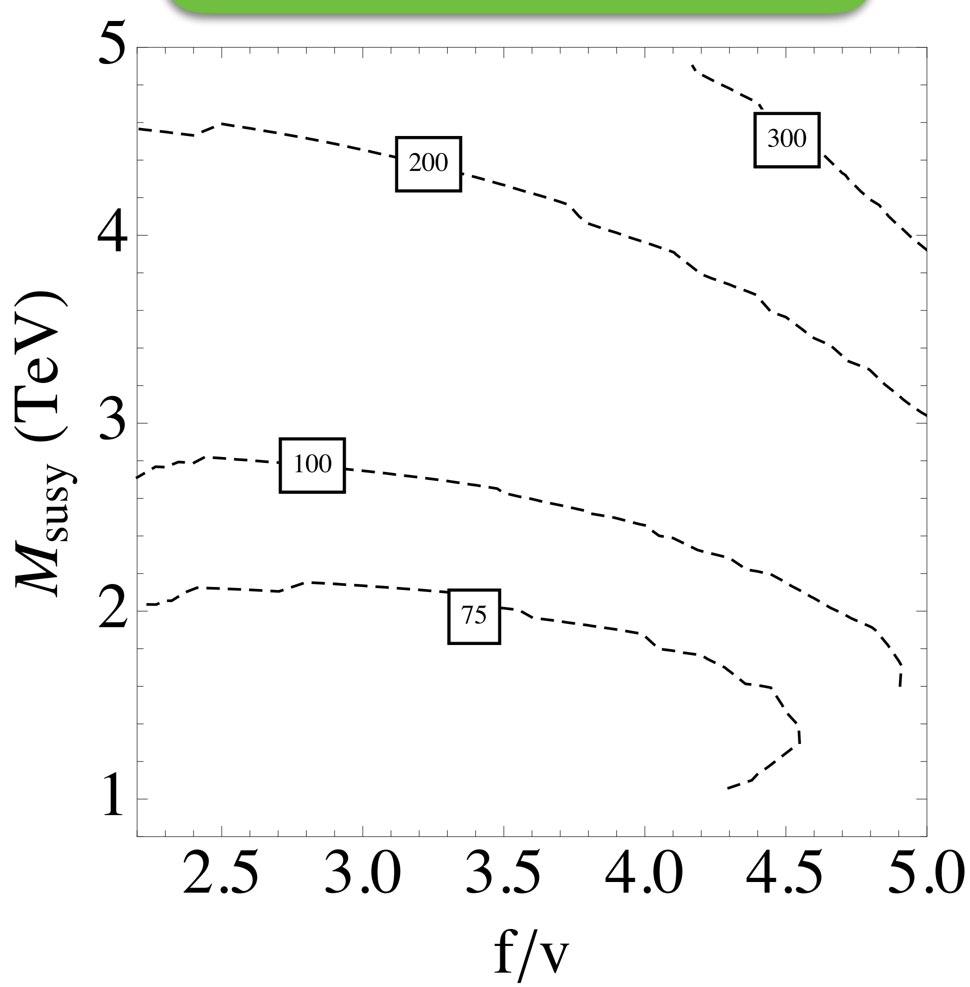

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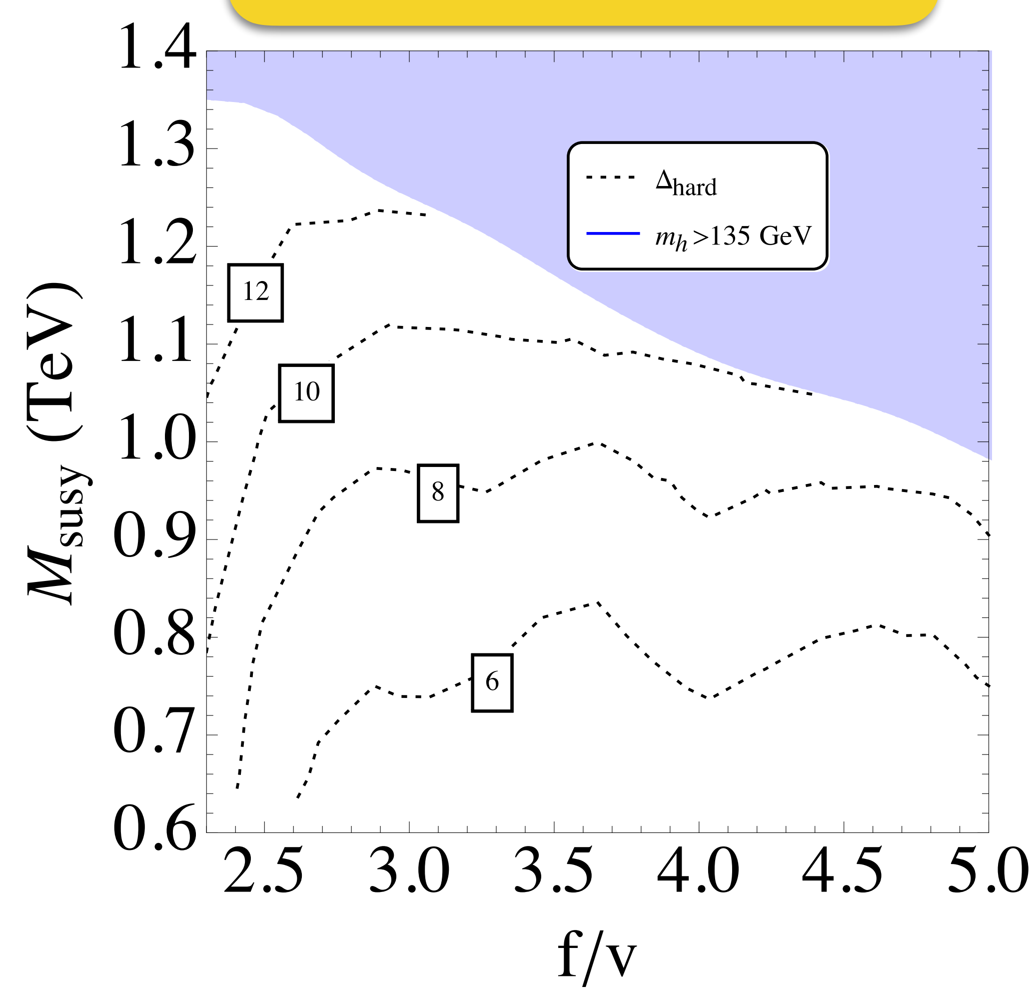
Hard breaking

in simplest realization



10% tuning

colored states within LHC reach
[because of Higgs mass constraint]

[also large f/v is fine]

Can we do better?

Extra negative κ_0
to reduce Higgs mass

can be generated adding A-B bidoublets

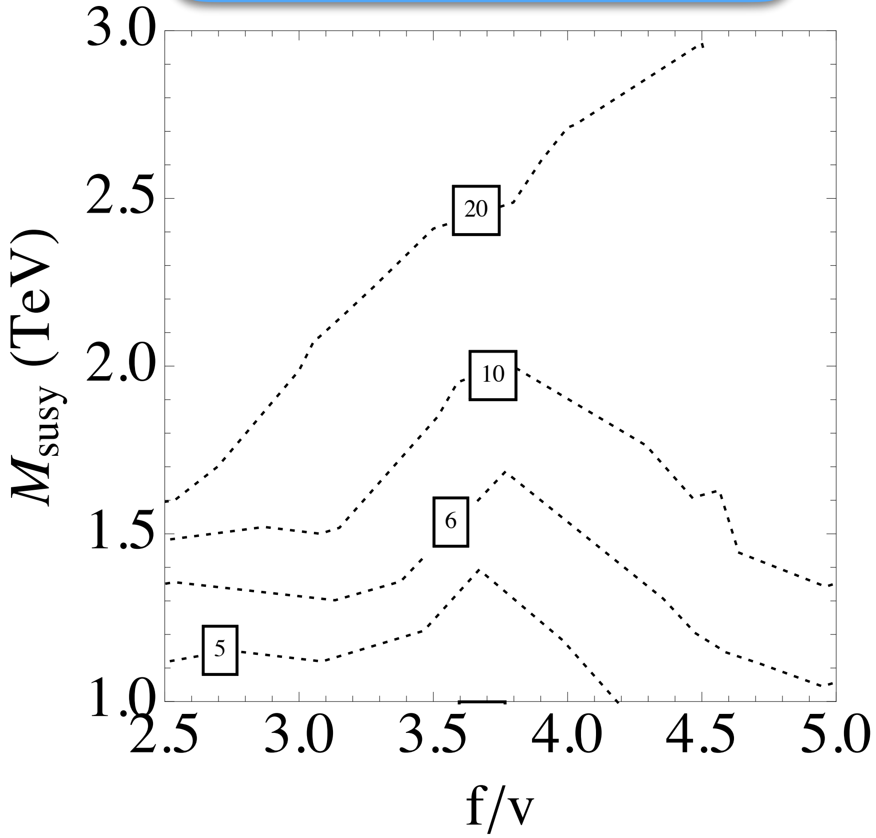
$$W = \lambda_d \Phi_d^{AB} H_u^A H_u^B \longrightarrow \kappa_0 = -\lambda_d^2 s_\beta^4$$

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

Preliminary result:

~10% FT with 2 TeV stops

Hard + Bidoublet



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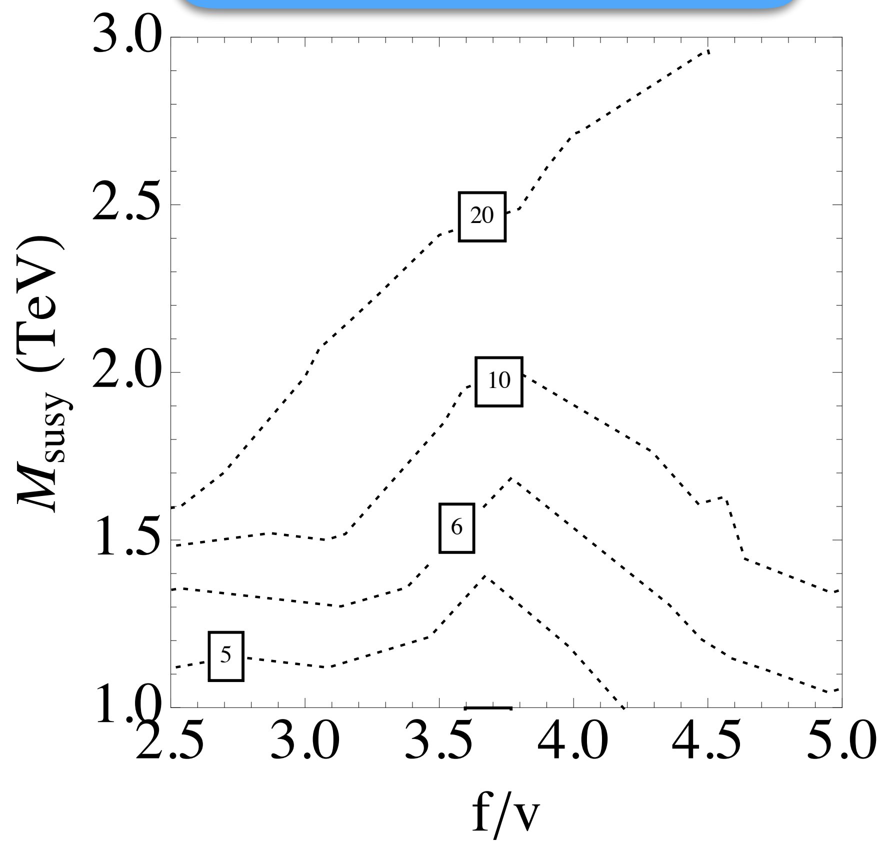


Can get positive quartic and positive correction to mass term from Z2 breaking threshold?

other/better solutions are in progress...

Twin SUSY
@ LHC

Higgs Spectrum

Twin SUSY ⇨ 4 Higgs doublet model

2 CP-odd neutral | 4 CP-even neutral | 2 charged

Spectrum controlled by 2 parameters: m_A, f

Lightest new state is **Twin Higgs: $h_T \sim \lambda_S f$** {dark}

1505.05488 Buttazzo, Sala & Tesi

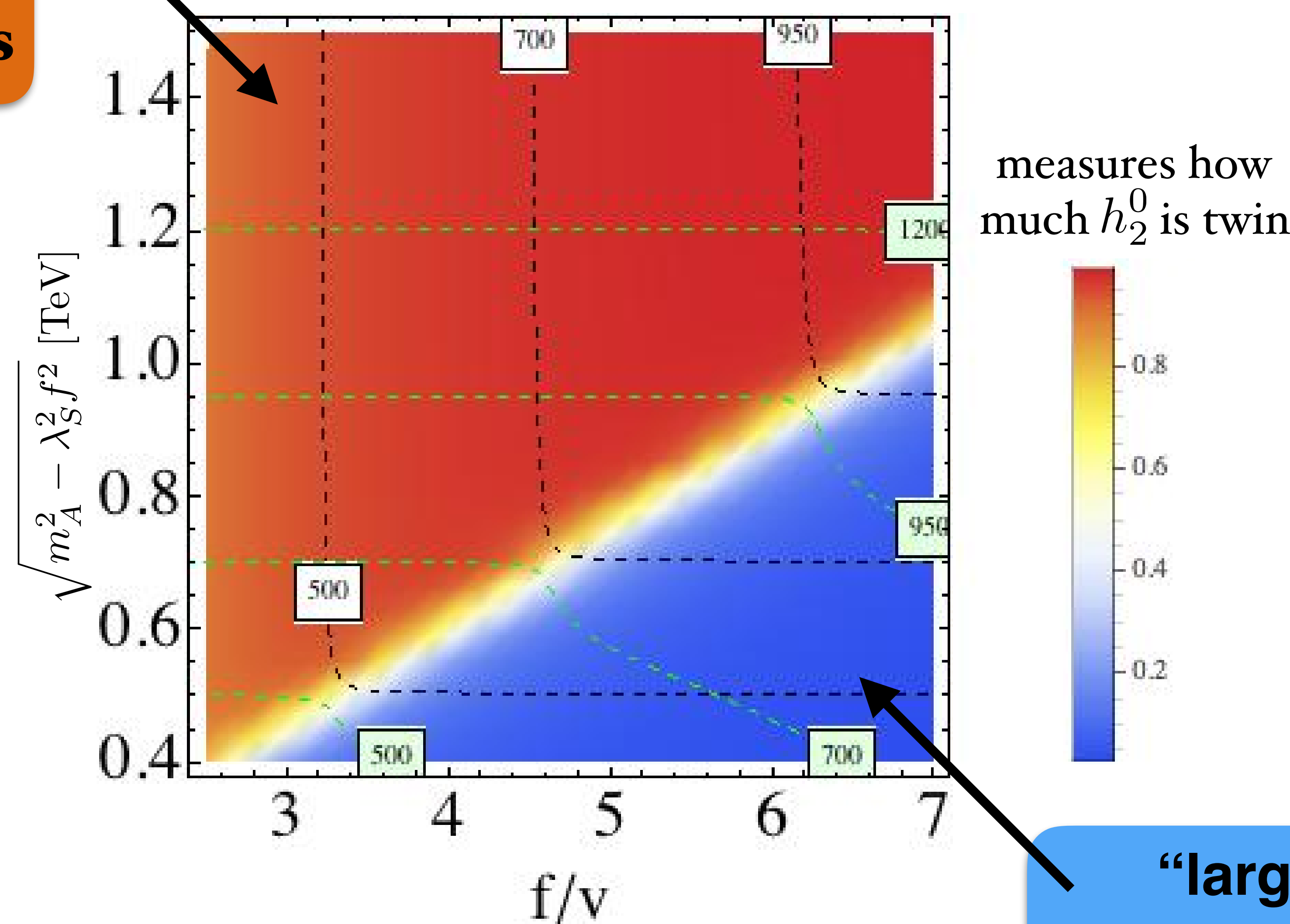
or **MSSM-like: $\{H, A, H^\pm\} \sim \sqrt{m_A^2 - \lambda_S^2 f^2}$** {visible}

1504.04630 Craig, D'Eramo, Draper, Thomas, Zhang
1605.08744 Craig, Hajer, Li, Liu, Zhang

The Next-To-Lightest Higgs

"low f" region
the twin is light

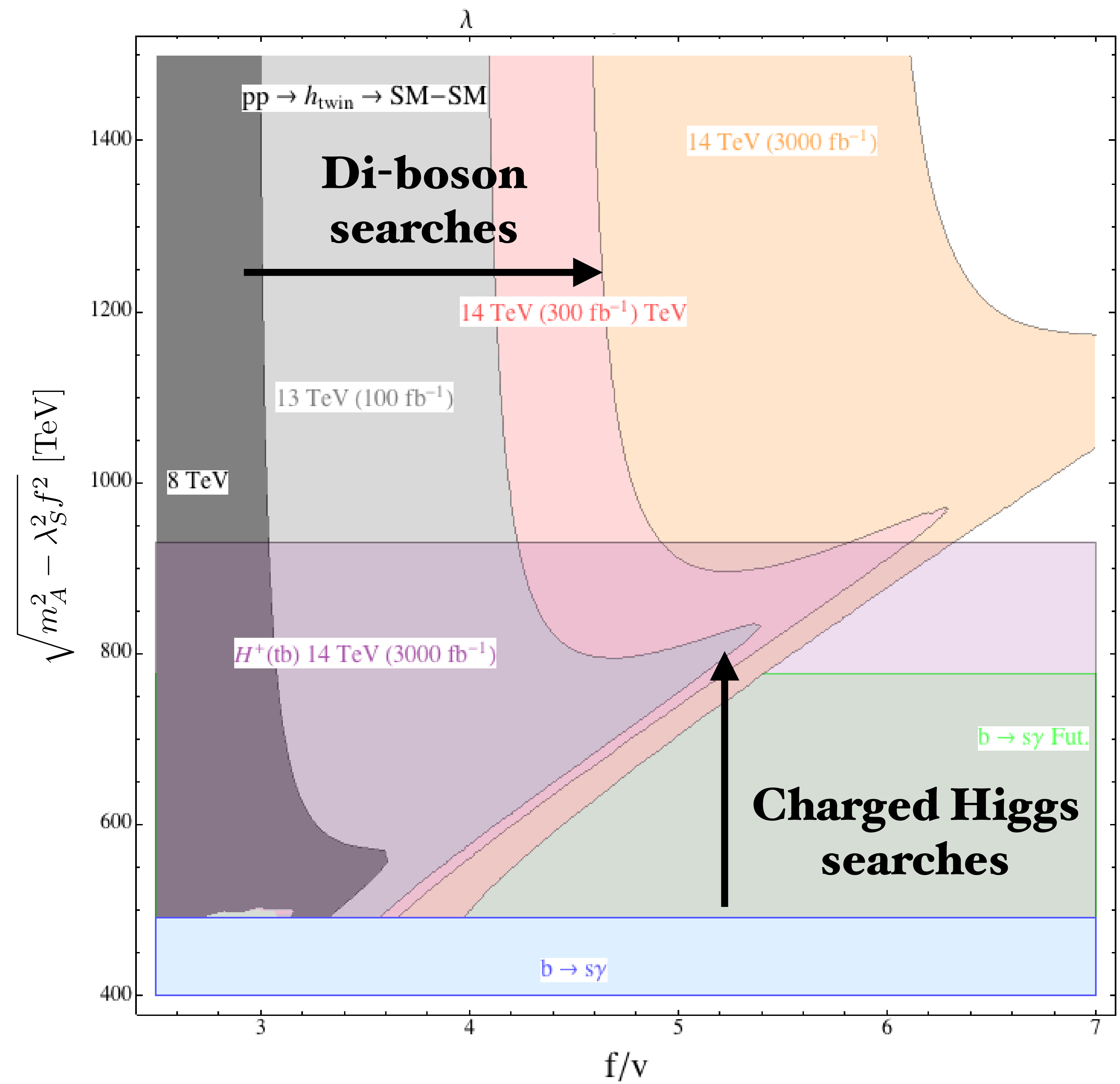
Di-boson searches



"large f" region
MSSM Higgses are light

MSSM (charged) Higgs searches

Higgs Searches



Summary

- Twin Higgs models with hard Z_2 breaking are rarely explored, but can reduce v/f tuning at the cost of increased Higgs mass

- SUSY models provide calculable UV completions, there are many options to get Higgs mass right and keep tuning low

- Large f phenomenology resembles MSSM at low t_β