Twin Higgs meets SUSY:
the soft, the hard and the ugly

Diego Redigolo

CERN, Geneva

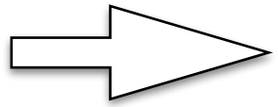
August 4th

based on **to appear with**

A. Katz, A. Mariotti, S. Pokorski and R. Ziegler

Neutral Naturalness
is by now a well established
paradigm to circumvent the null results at LHC
keeping the fine tuning ~10 %

General Lesson:

EXACT SYMMETRIES  COLORED TOP-PARTNERS

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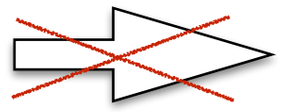
General Lesson: ACCIDENTAL SYMMETRIES  COLORED TOP-PARTNERS

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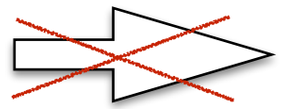
General Lesson: ACCIDENTAL SYMMETRIES  COLORED TOP-PARTNERS

Twin Higgs
is the *easier* implementation

0506256 Chacko, Goh and Harnik

easier= 4d description /accidental symmetry enforced by a Z_2
exchanging two copies of the SM

(less easy ways have been explored 0609152 Burdman, Chacko, Goh and Harnik
1411.7393 Craig, Knapen, Longhi
1601.07181 Craig, Knapen, Longhi,Strassler
1601.07181 Cohen, Craig, Lou, Pinner

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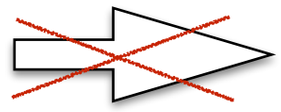
General Lesson: ACCIDENTAL SYMMETRIES  COLORED TOP-PARTNERS

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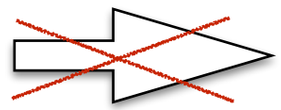
General Lesson: ACCIDENTAL SYMMETRIES  COLORED TOP-PARTNERS

2 challenges (in the original Twin already)

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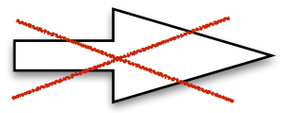
General Lesson: ACCIDENTAL SYMMETRIES  COLORED TOP-PARTNERS

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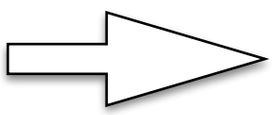

EXPLORING THE PARAMETER SPACE of the Twin Higgs

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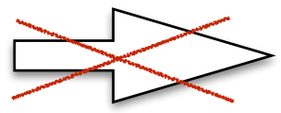
General Lesson: ACCIDENTAL SYMMETRIES  COLORED TOP-PARTNERS

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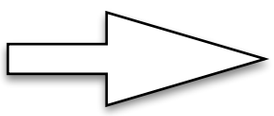

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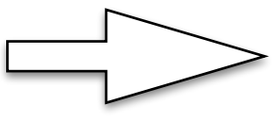
★ UV COMPLETIONS of Twin Higgs constructions:



FINE TUNING vs LHC searches: How long to exclude 10% FT @ LHC?

Plan of the Talk:

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A fresh look
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the role of Z_2-breaking operators: **soft** (relevant) *vs* **hard** (marginal)

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beyond "soft" Twin SUSY

- *"hard"* Twin SUSY vs $m_h = 125$ TeV
- *"ugly"* Twin SUSY & fine-tuning comparison

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Twin SUSY @ LHC

Twin Higgs vs MSSM-like Higgs searches

At least 1 extra Higgs accessible at LHC14 with FT~10%

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: $H_A \longleftrightarrow H_B \ \ldots$

the rest of the spectrum

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

Affect a lot of phenomenology both cosmological and at collider but we leave it unspecified in our discussion... see talks by Nathaniel and Roni

Linear sigma model

$$\underbrace{\lambda(|H_A|^2+|H_B|^2-f^2)^2}_{V^{U_4}} + \underbrace{\kappa(|H_A|^4+|H_B|^4)}_{V^{\psi_4,Z_2}} + \underbrace{\tilde{\mu}^2|H_A|^2+\rho|H_A|^4}_{V^{\psi_4,\not{Z}_2}}$$

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$\lambda > 0 \quad f^2 > 0$

$U(4)$ spontaneously broken

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Z_2 preserved ⟶ maximal mixing

$s_\theta = 1/\sqrt{2} > 0.45$

excluded!

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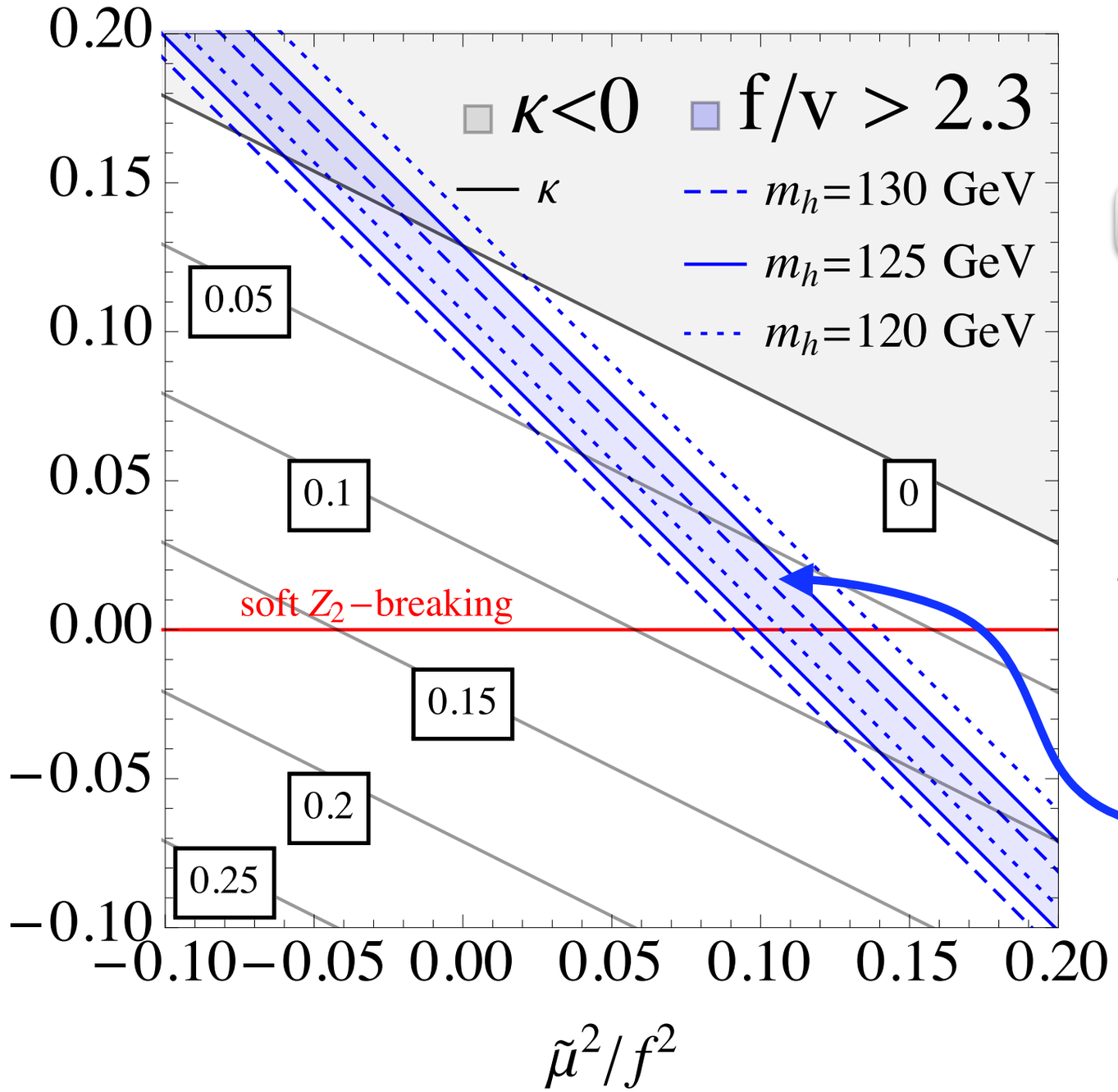
$s_\theta \approx v/f > 0.45$

$f > 2.3v \approx 400$ GeV

viable!



THE TWIN HIGGS on a plane…

4 parameters: $\{\tilde{\mu}^2, \kappa, \rho, f\}$

- 2 constraints: EWSB+ HIGGS

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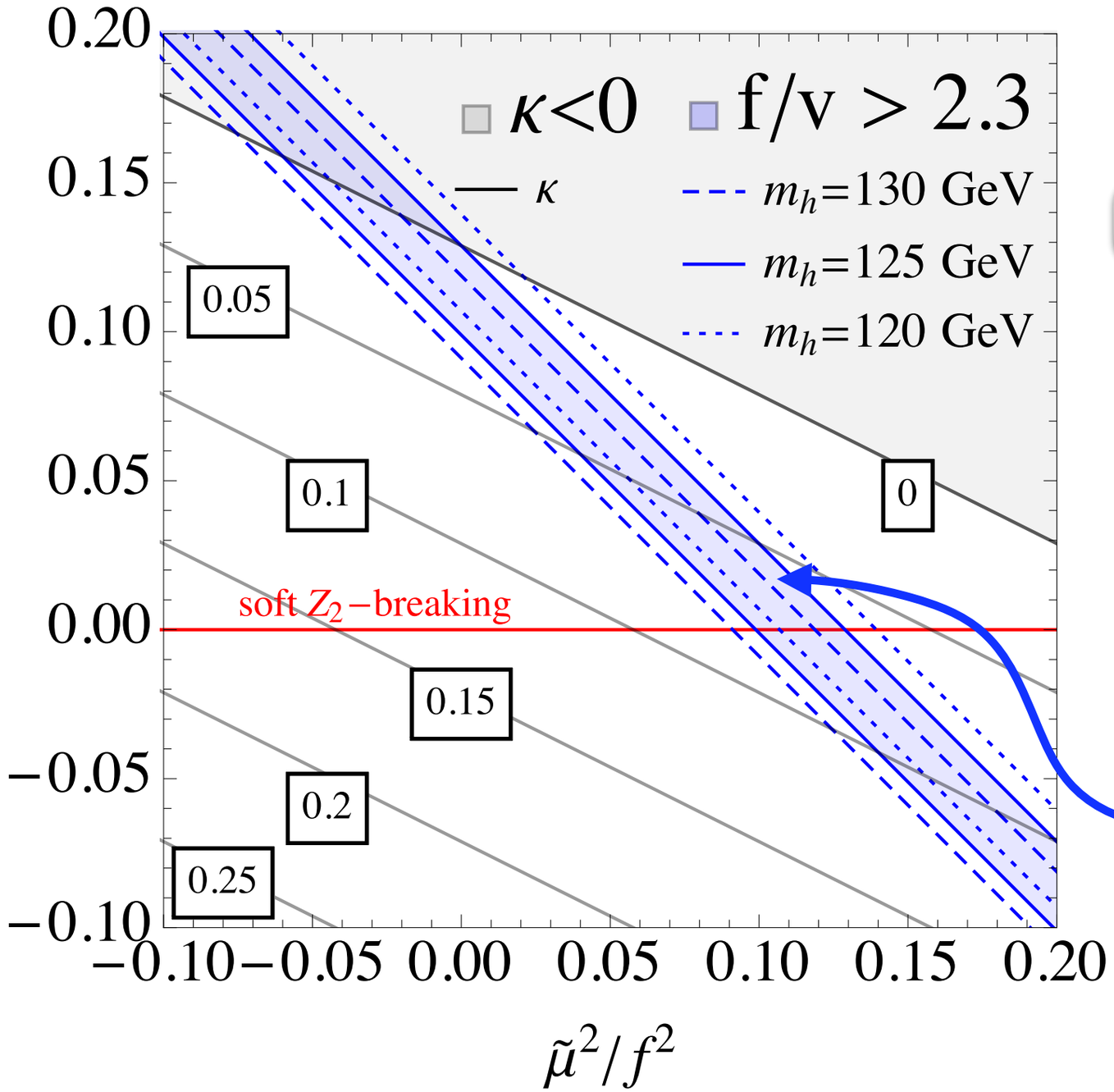
2 dimensional par. space

with the constraint $f/v > 2.3$



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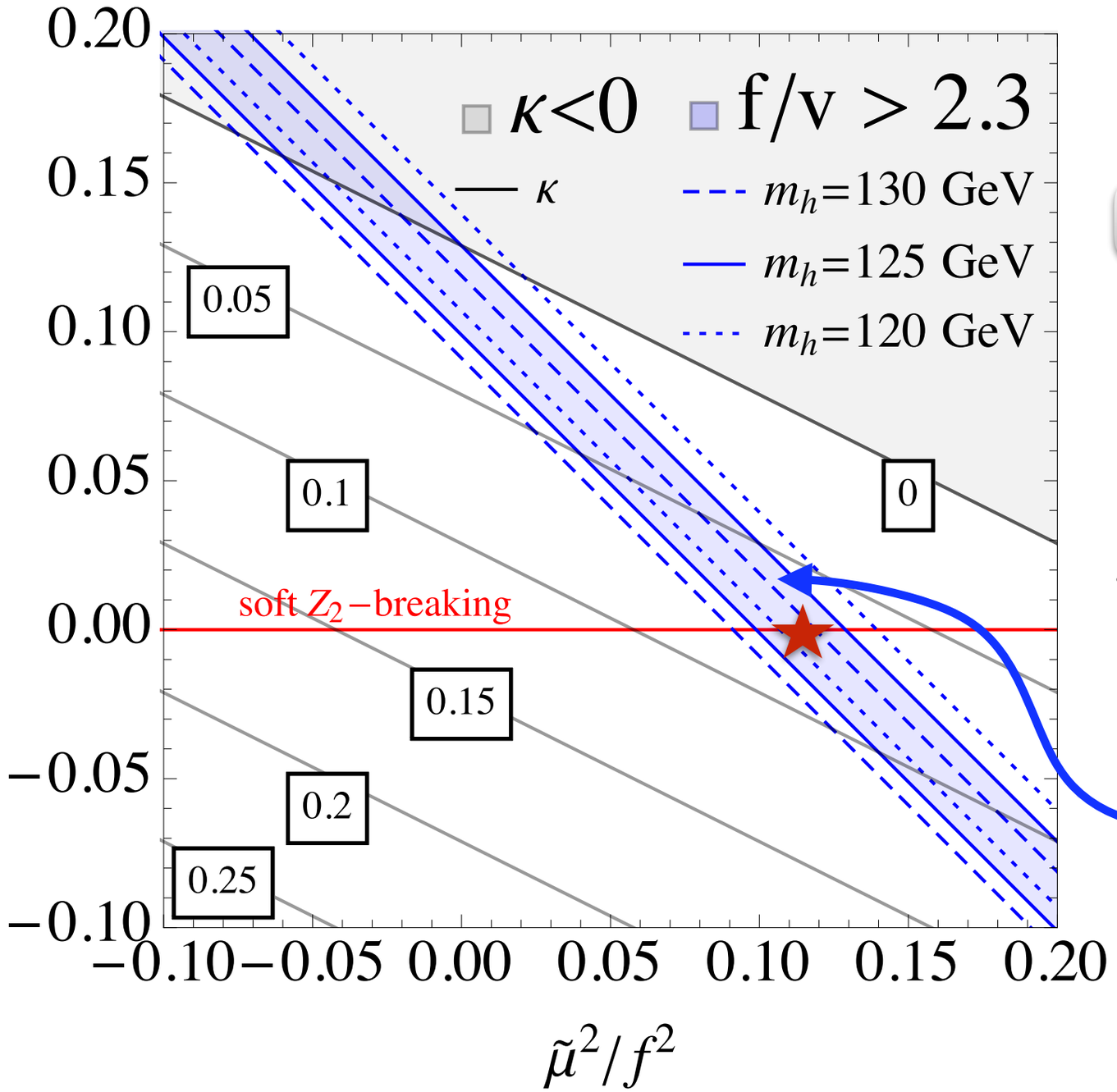

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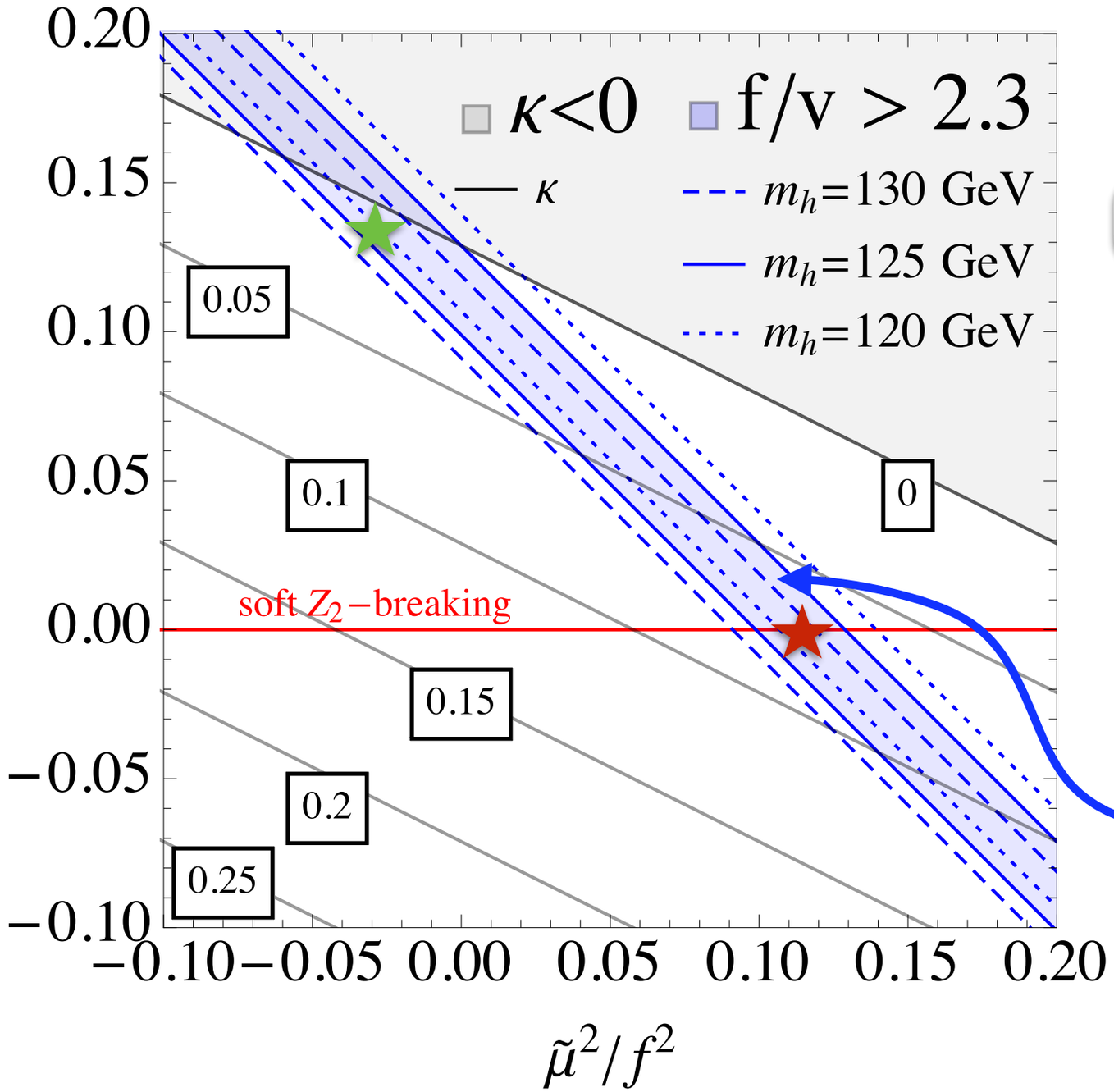

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★ hard-breaking: $\tilde{\mu}^2/f^2 \ll \rho$ tuning $\kappa \ll \rho$ to get m_h

Including quantum corrections…

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

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

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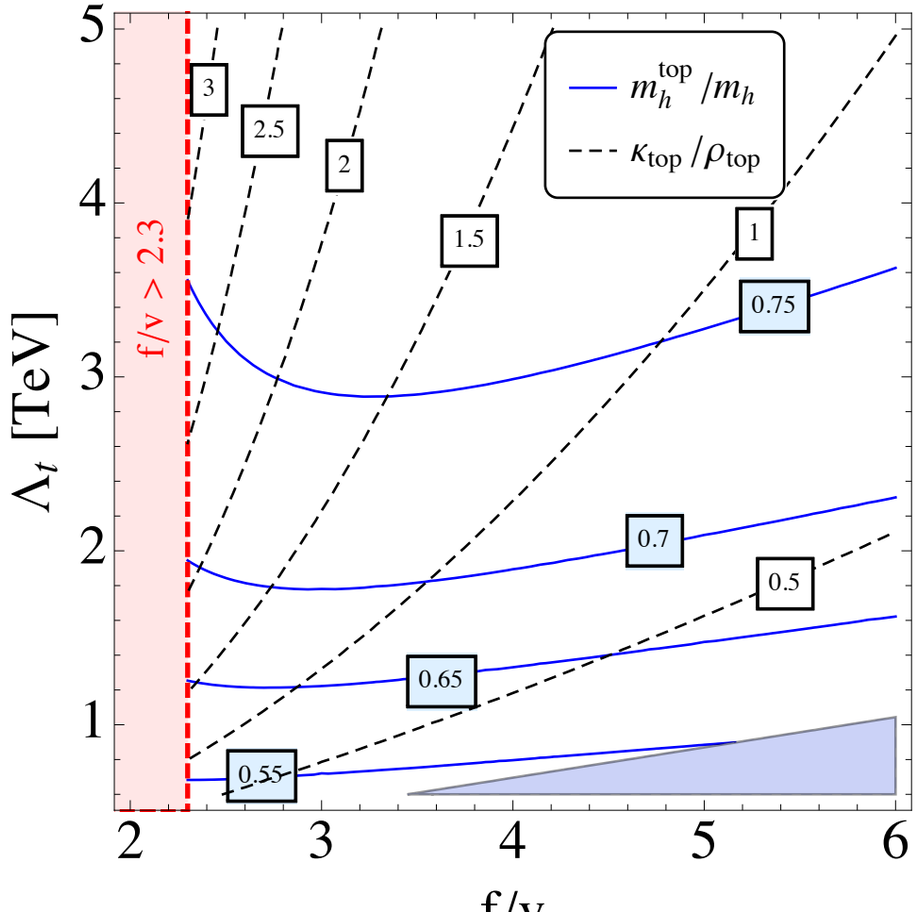

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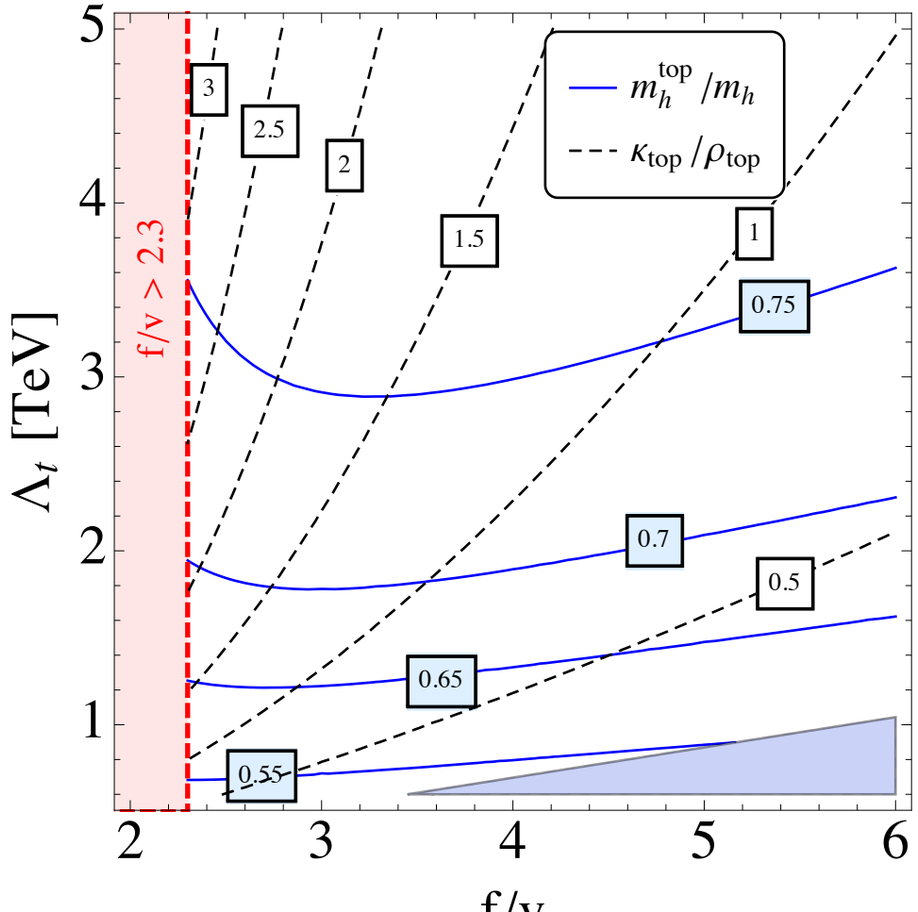
disclaimer about FT

We are neglecting the tuning f vs cut-off in the effective theory.

This can be reliably computed only after UV completion!



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$$\Delta^{\text{soft}}_{v/f} \approx 1 - \frac{f^2}{2v^2}$$

low fine-tuning favours small f

Extra positive κ_0 to get $m_h = 125$ GeV

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the gain in fine-tuning is larger at large f

the gain in fine-tuning correspond to an enhancement of the Higgs mass

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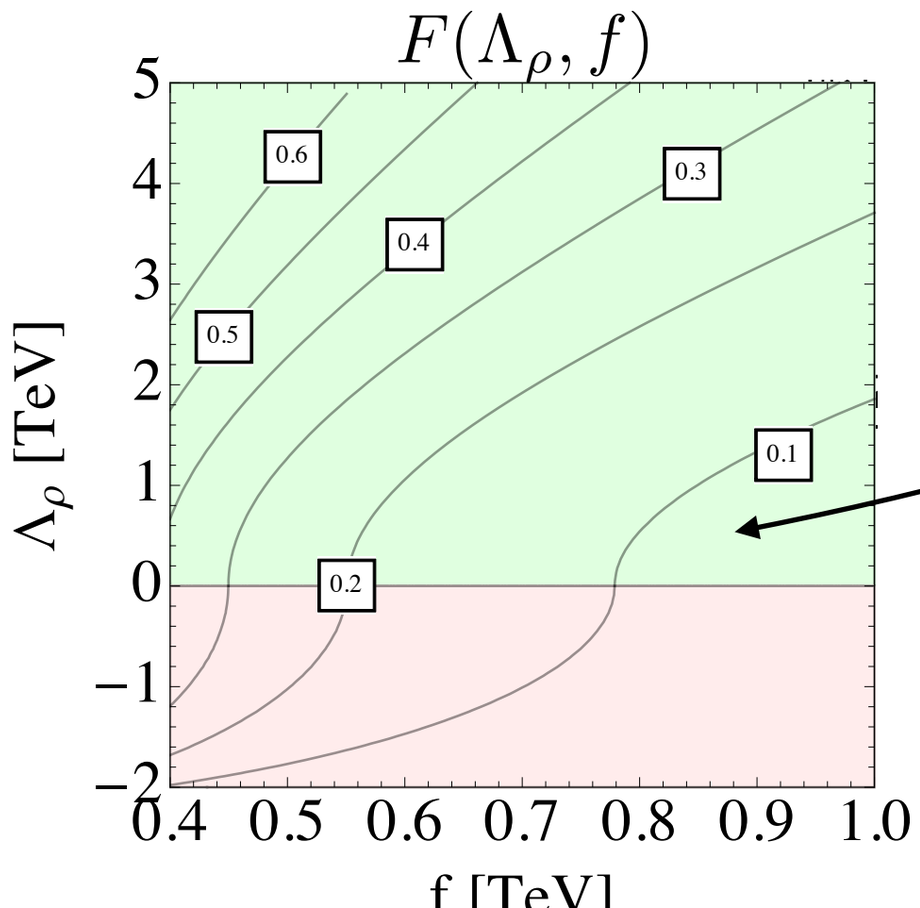
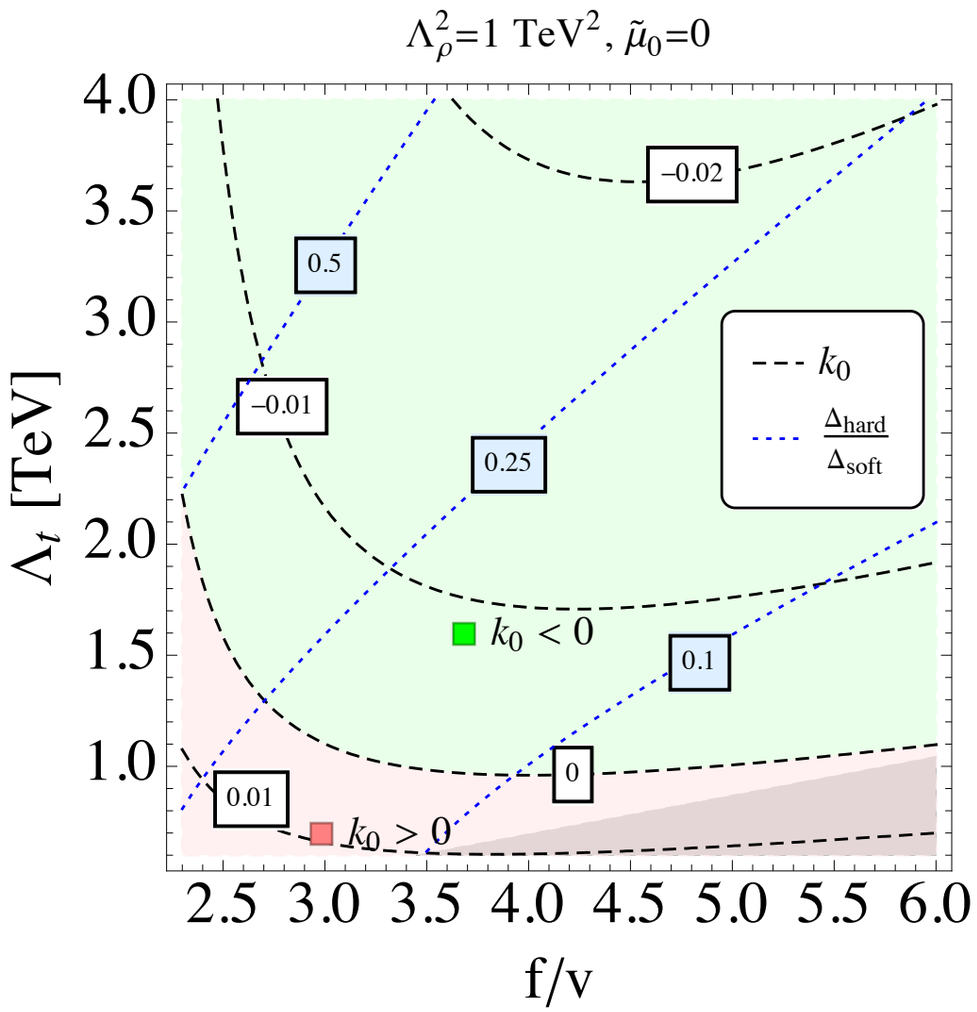


3 (ugly) ways of making hard-breaking viable:

getting $m_h = 125$ GeV

Extra negative κ_0



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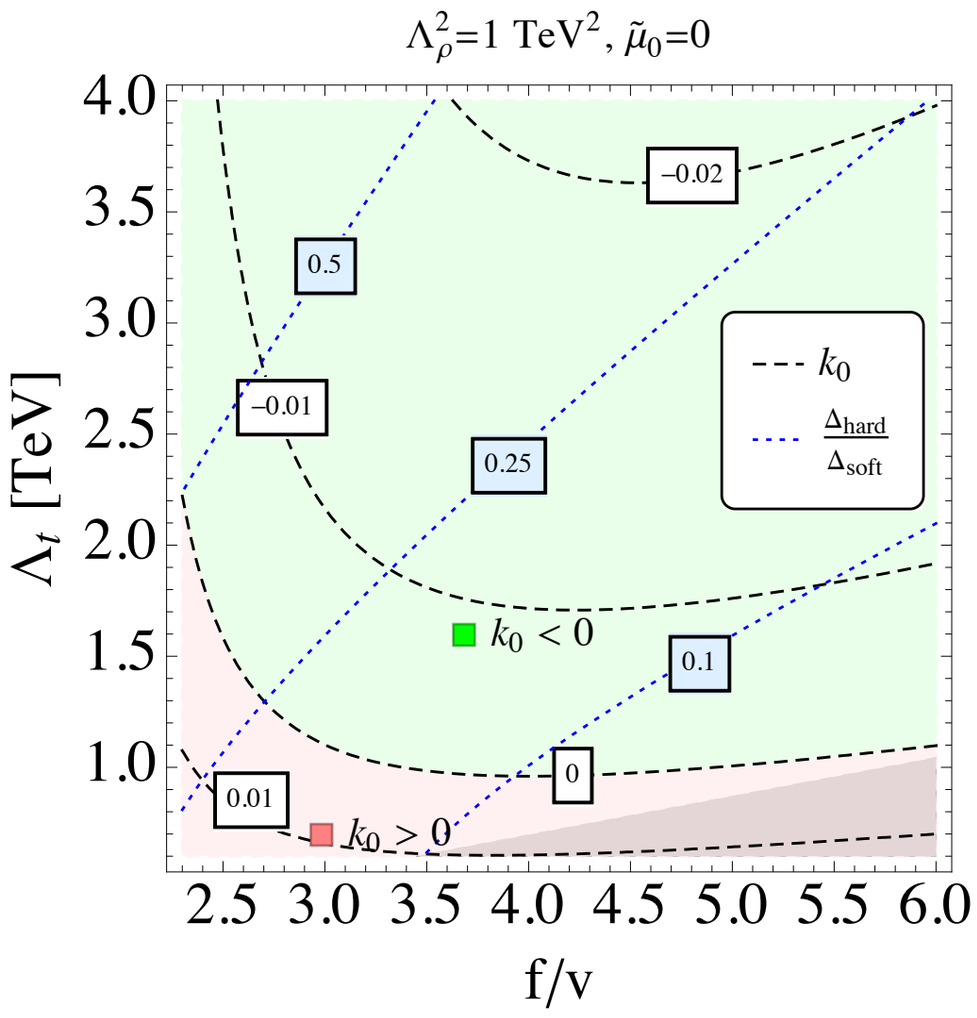
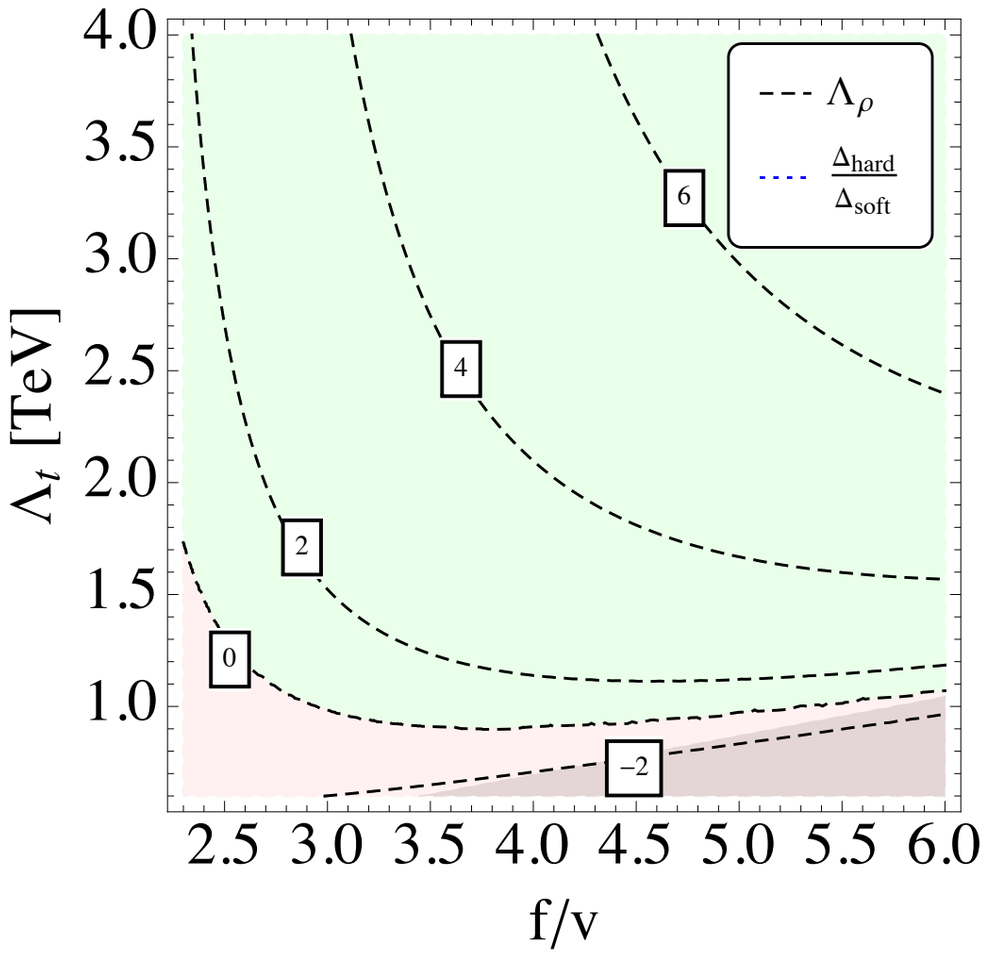


What is the UV threshold parametrized by Λ_ρ?



O(1) differences with Λ_t can accommodate the Higgs

WARNING: the sign is crucial!

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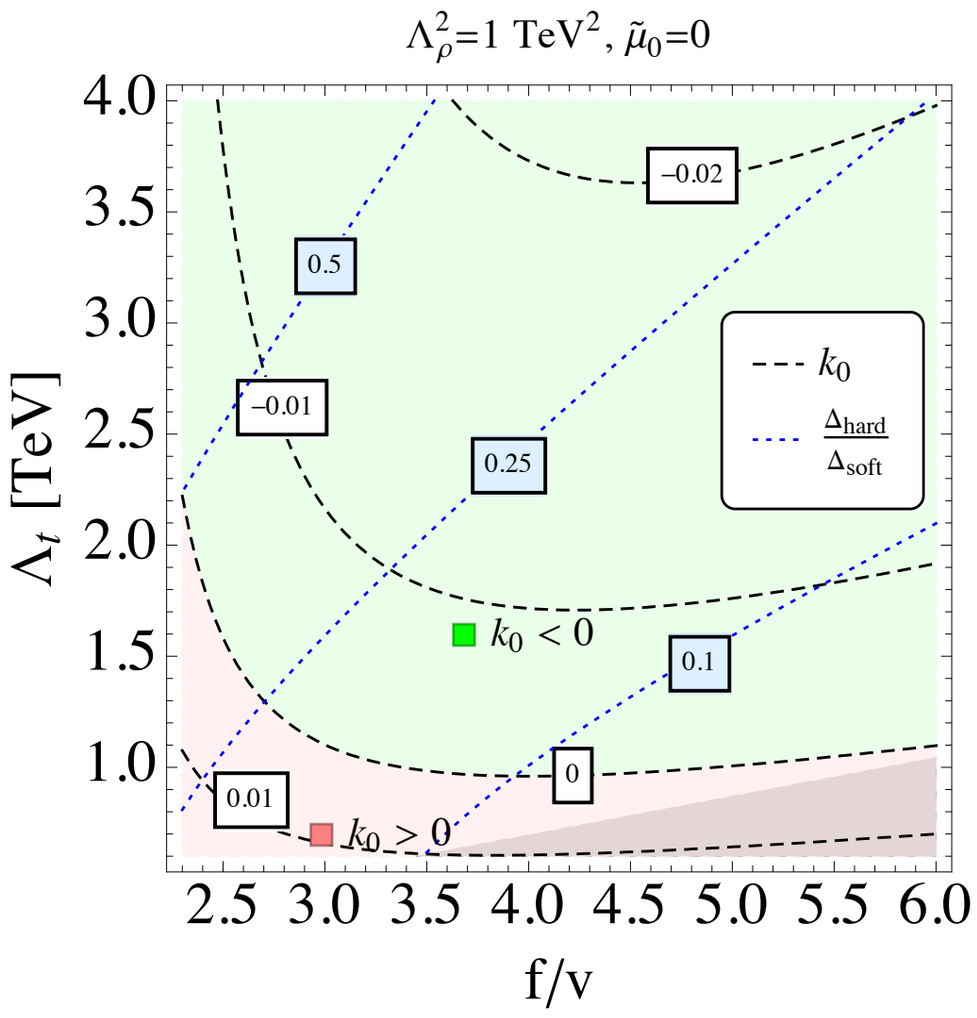

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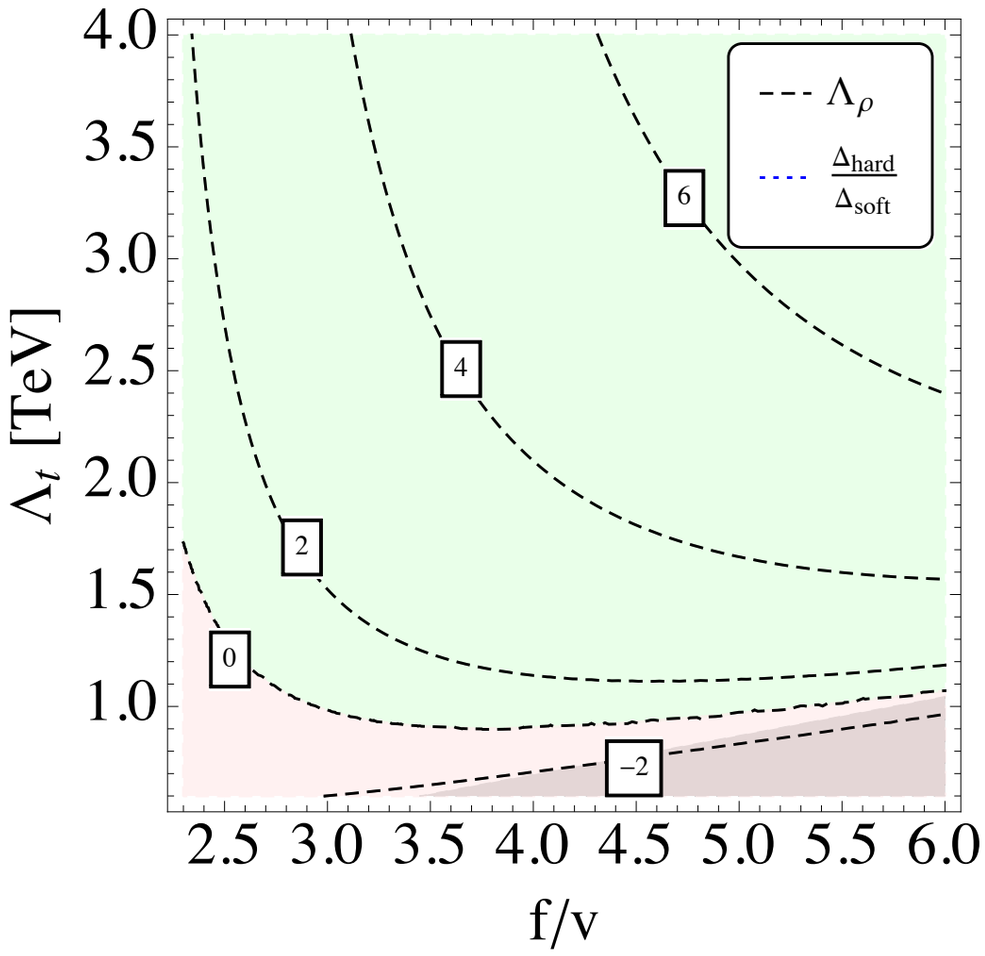

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One can also introduce back soft-breaking at tree level...

SUSY
UV completions

Exploring UV complete versions of Neutral naturalness

Twin Higgs needs a UV completion

(Especially true if hard-breaking is present)

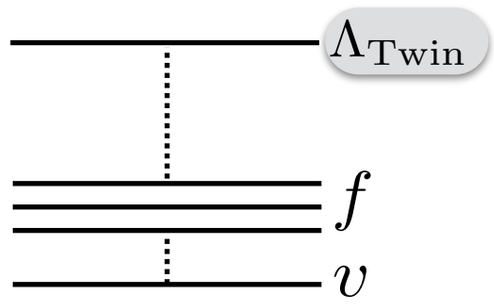
SUSY needs some help:

LITTLE FINE-TUNING PROBLEM

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

WHERE IS EVERYBODY?

M_s controls the scale of colored states



Exploring UV complete versions of Neutral naturalness

Twin Higgs needs a UV completion

(Especially true if hard-breaking is present)

SUSY needs some help:

LITTLE FINE-TUNING PROBLEM

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

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what happens if

$$\Lambda_{\rm Twin} = M_s$$

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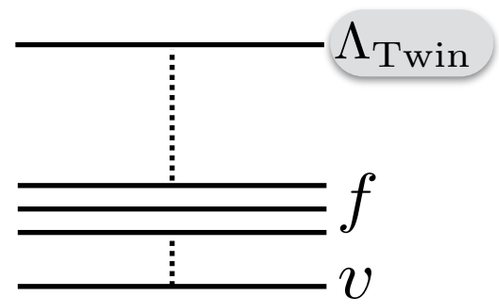

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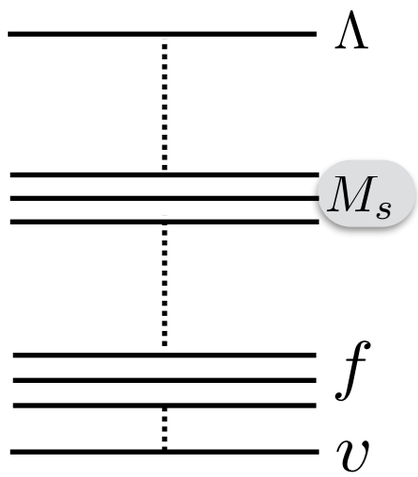

ameliorates
fine-tuning

“ Twin Higgs ”

Higgs is PGB of accidental global symmetry

top partners uncolored

provides
calculable UVC

Supersymmetry

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Supersymmetry

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 5-10 % !?)

matching the SUSY potential
to the Twin Higgs linear sigma model:

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

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

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

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★ quartic from non-dec. F-terms

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

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the nature of the singlet sector determines the nature of the cut-off Λ_ρ

Compute the fine-tuning with respect to the UV cut-off

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

Two sources of tuning

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

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

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

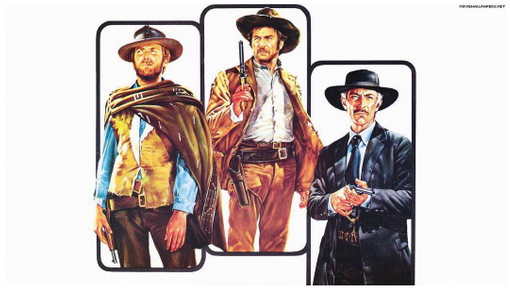
SOFT Twin SUSY: the factorization of the FT measure is exact

The only gain in FT $\sim 1/\lambda$ as a consequence of double protection

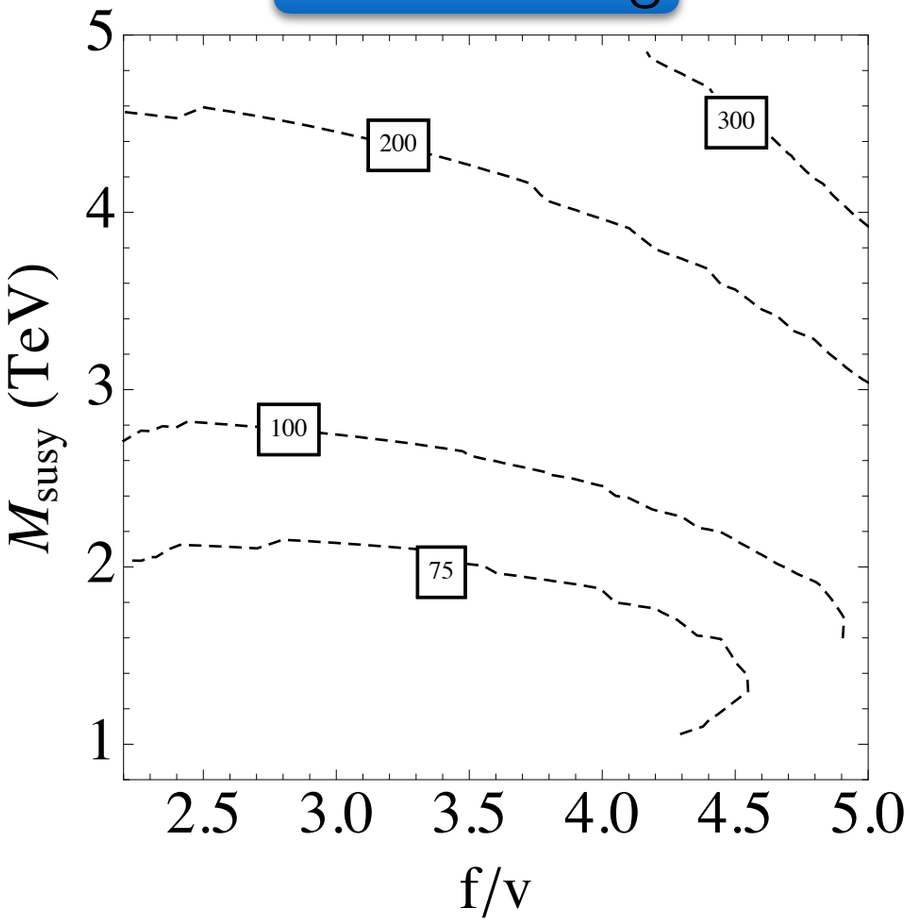
HARD Twin SUSY: the factorization does not hold anymore

How much of the gain we saw in the effective theory survives UV completion?

3 simple models: soft, hard & ugly



soft-breaking

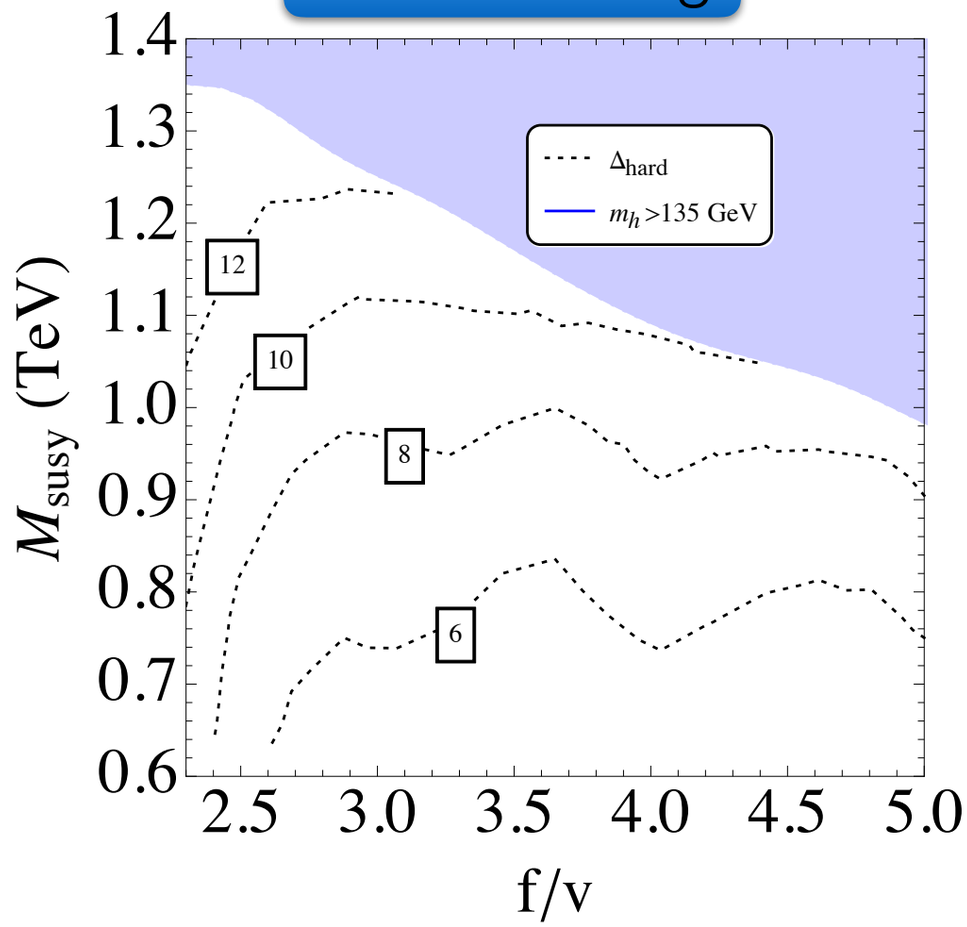


1% tuning

colored states decoupled from LHC

1312.1341 Craig & Howe

hard-breaking



10% tuning

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

$$W = \lambda_A S_A H_u^A H_d^A$$

The UV threshold gives a NEGATIVE mass term
at 1-loop

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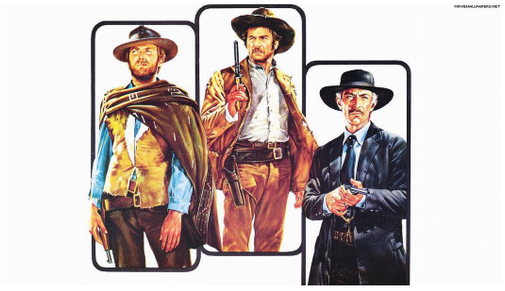
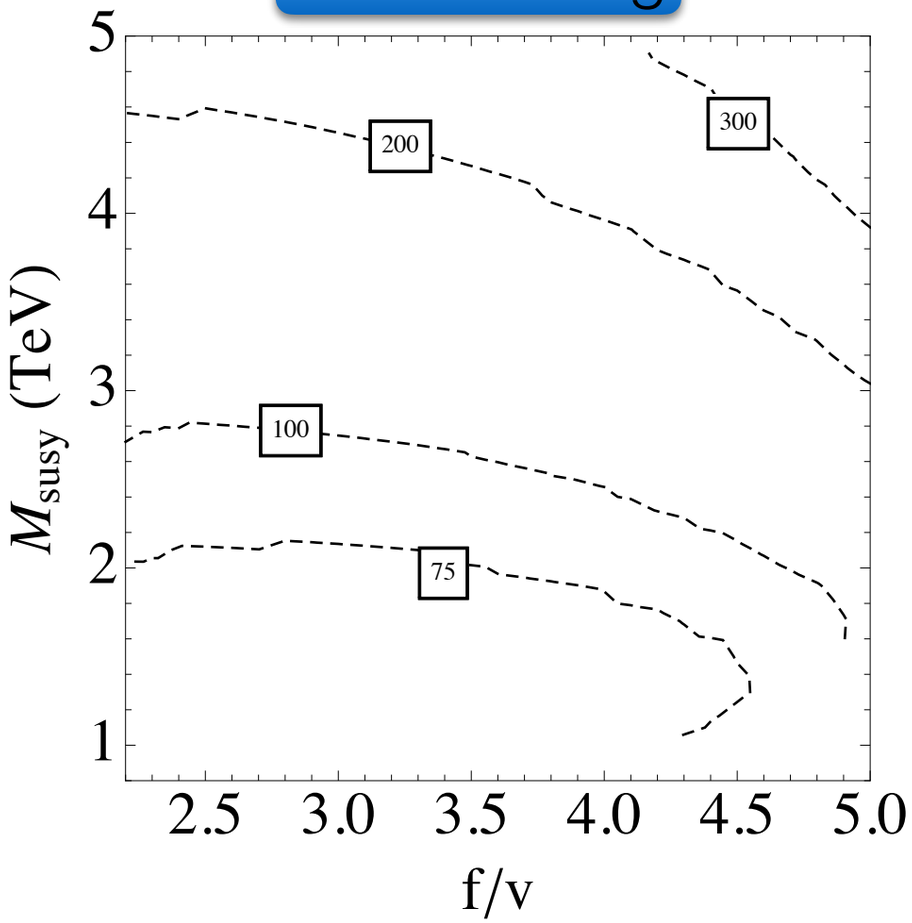


soft-breaking



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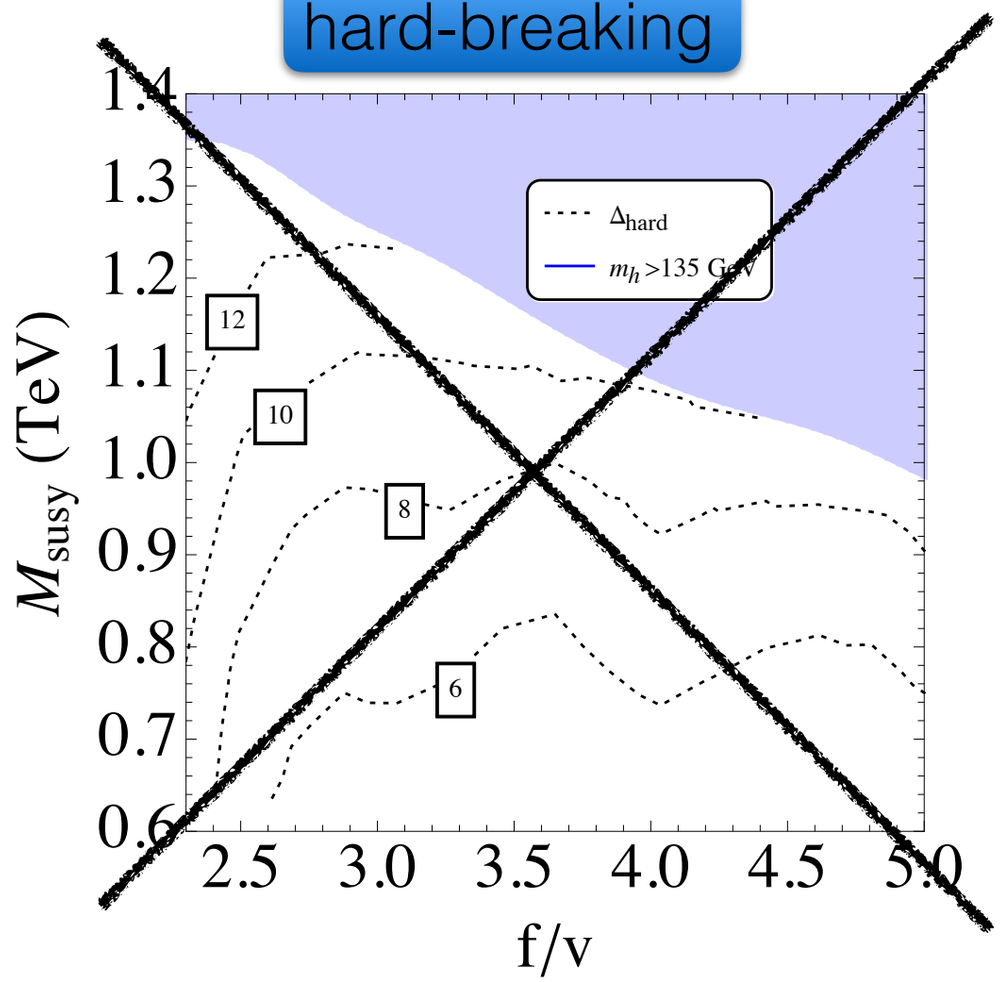

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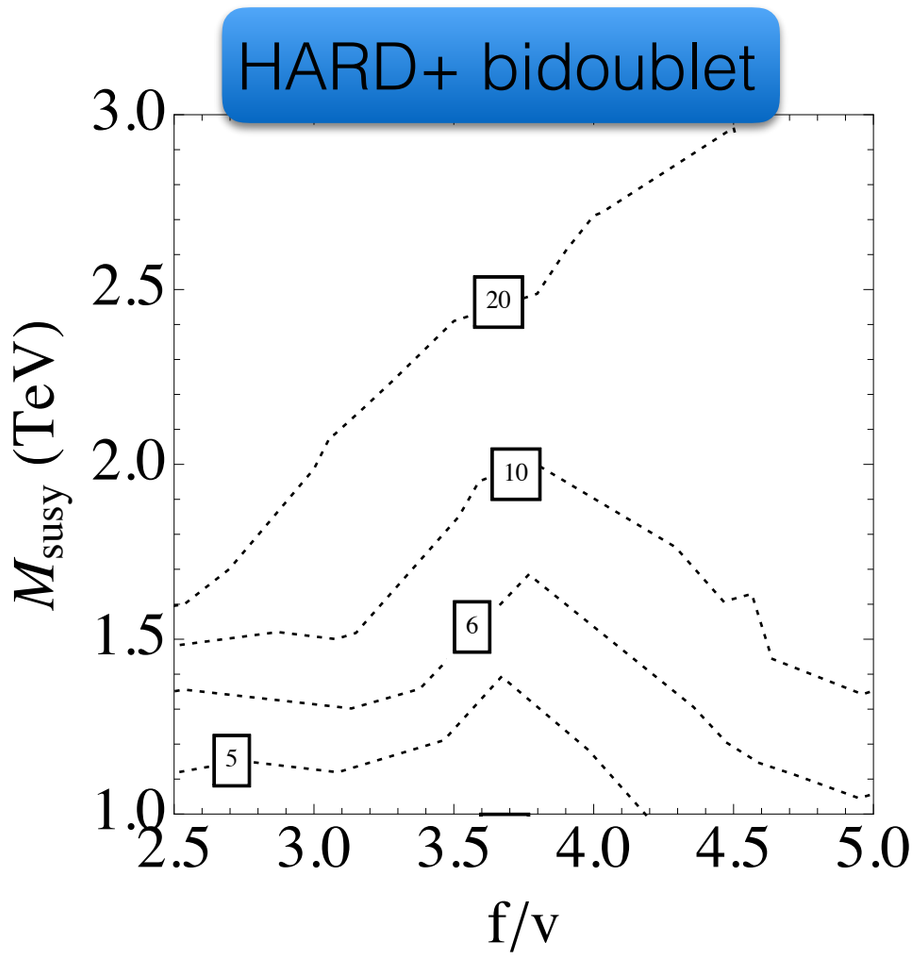
Can we do better?

Extra negative κ_0 can be generated adding AB bi-doublets

$$W = \lambda_d \Phi_d^{AB} H_u^A H_u^B \quad \Rightarrow \quad \kappa \to \kappa - \lambda_d^2 s_\beta^4$$

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



PRELIMINARY RESULT:~10% FT with 2 TeV stops

other/better solutions are in progress..

Can we get a positive quartic and a positive threshold correction to the mass term at 1-loop?

Twin SUSY

@

LHC

Neutral Naturalness ⇒ Extended Higg Sector

Twin SUSY ⇒ 4 Higgs doublet model

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

Spectrum controlled by 2 parameters: m_A f

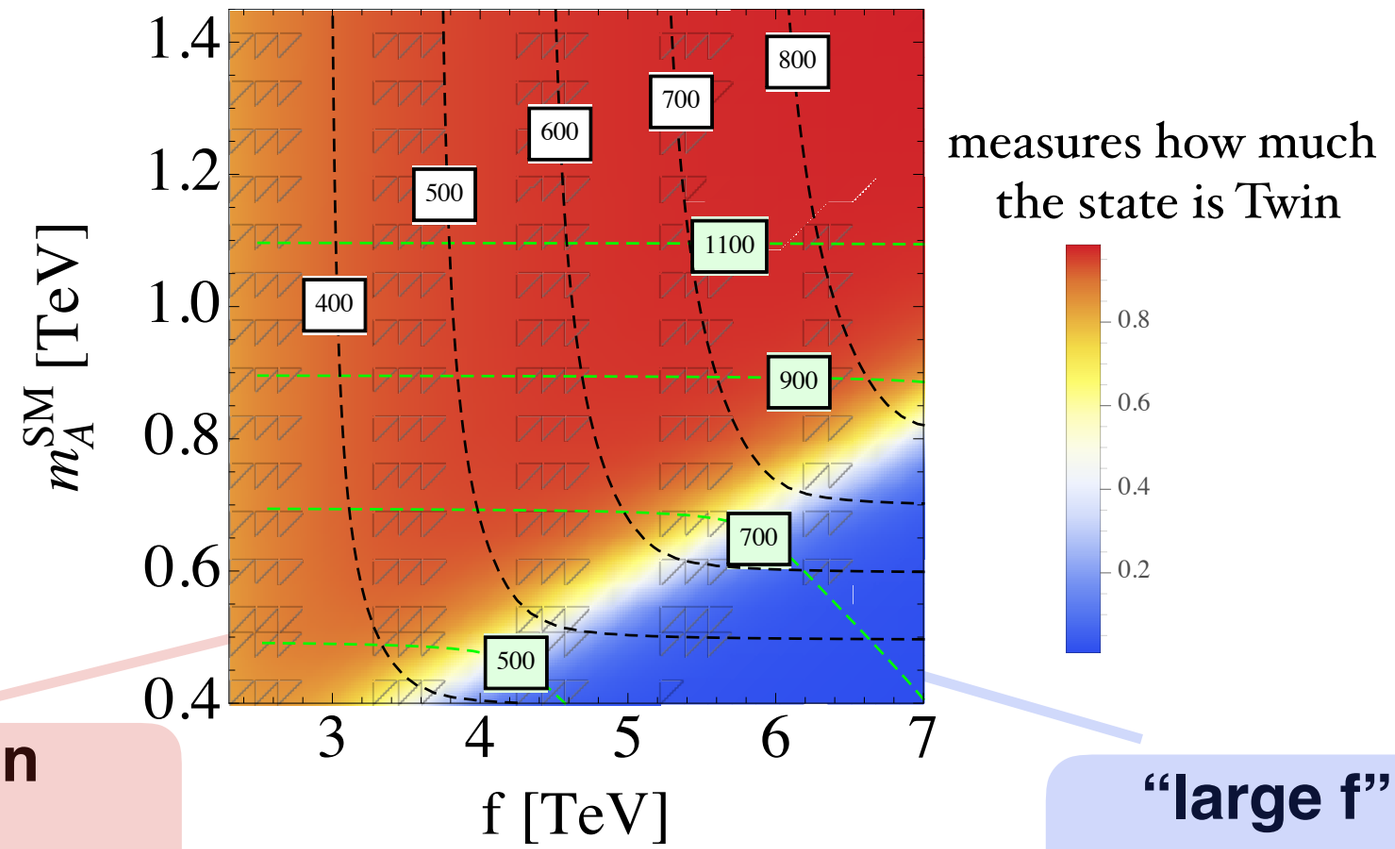
CAN WE OBSERVE THESE EXTRA HIGGSES @ LHC?

$$\begin{cases} h_2^0 \sim \sqrt{\lambda} f & \text{The radial mode (Twin Higgs) decays mostly into gauge bosons} \\ \{A_{SM}\,,\ H_{SM}\,,\ H_{SM}^{\pm}\} \sim \sqrt{m_A^2 - \lambda f^2} & \end{cases}$$

1505.05488 Buttazzo, Sala & Tesi

1504.04630
Craig, D'Eramo, Draper, Thomas, Zhang

1605.08744
Craig, Hajer, Li, Liu, Zhang



measures how much the state is Twin

“low f” region

the radial mode is light

diboson searches
vs
Neutral naturalness

“large f” region

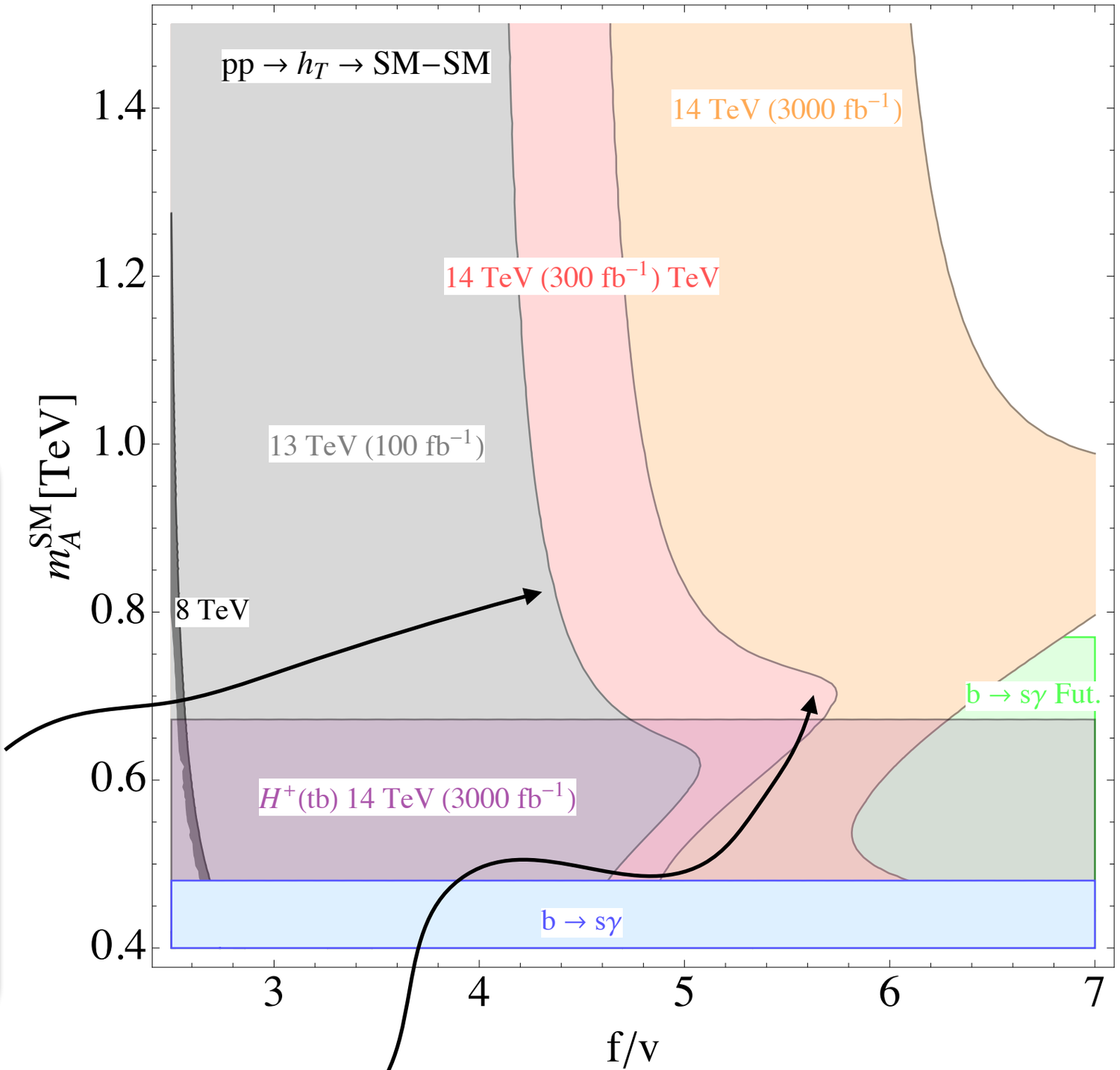
MSSM-like Higgses light

MSSM Higgs searches
vs
(neutral) naturalness

REMARK: Soft Twin SUSY prefers low f

Hard Twin SUSY gets lower fine tuning with higher f

PROSPECTS for TWIN SUSY



END of 2018: f/v>4

to close f/v>4
we need more time

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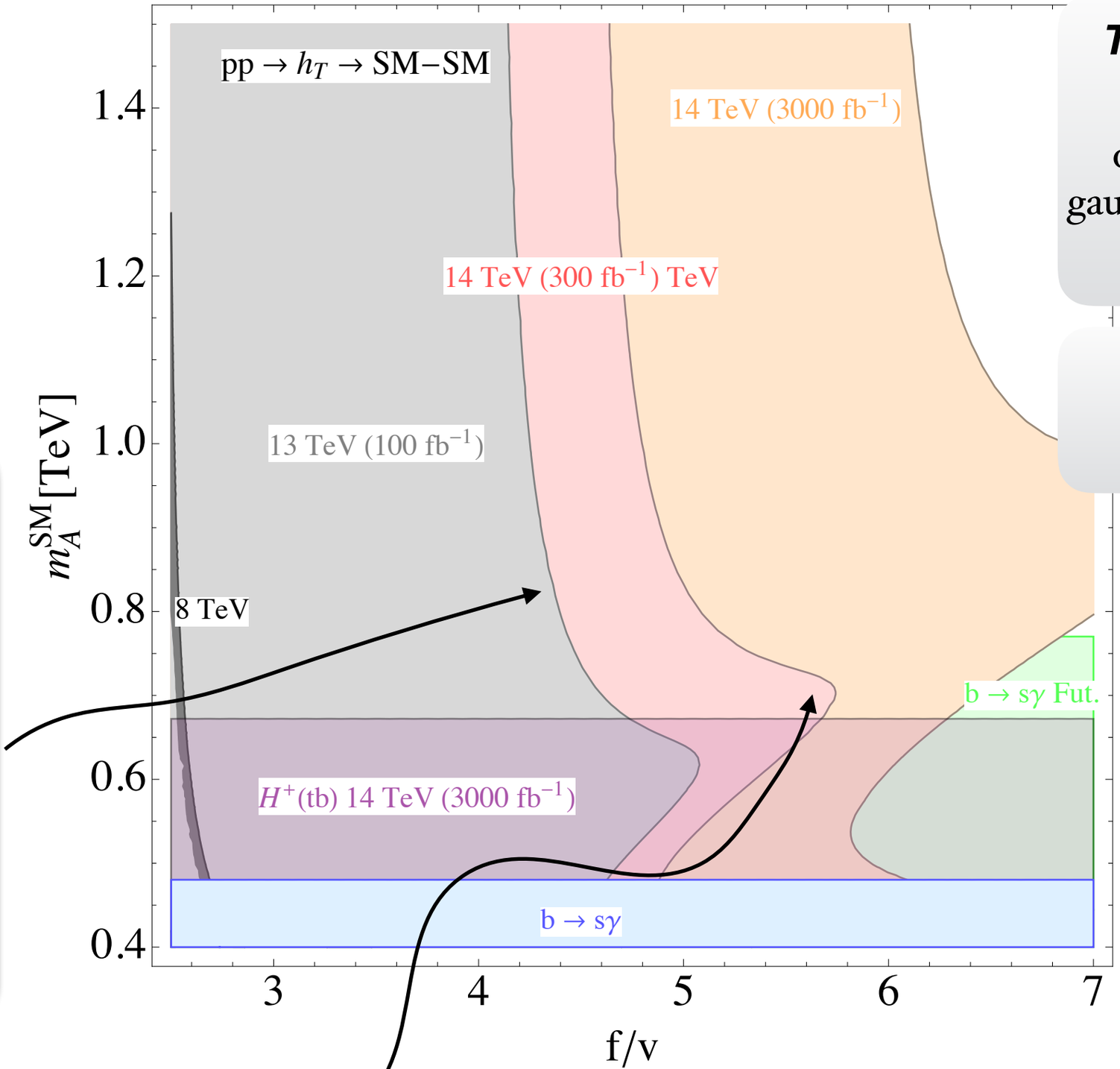

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Twin Higgs searches in SUSY:

for a perturbative quartic the decay of the radial mode to dark gauge bosons are kinematically closed

The width is fully dominated by decay into gauge bosons and SM higgs

$t\bar{t}$ is subleading but non-negligible

ZZ searches have the best reach/constraint

1504.00936
CMS collaboration

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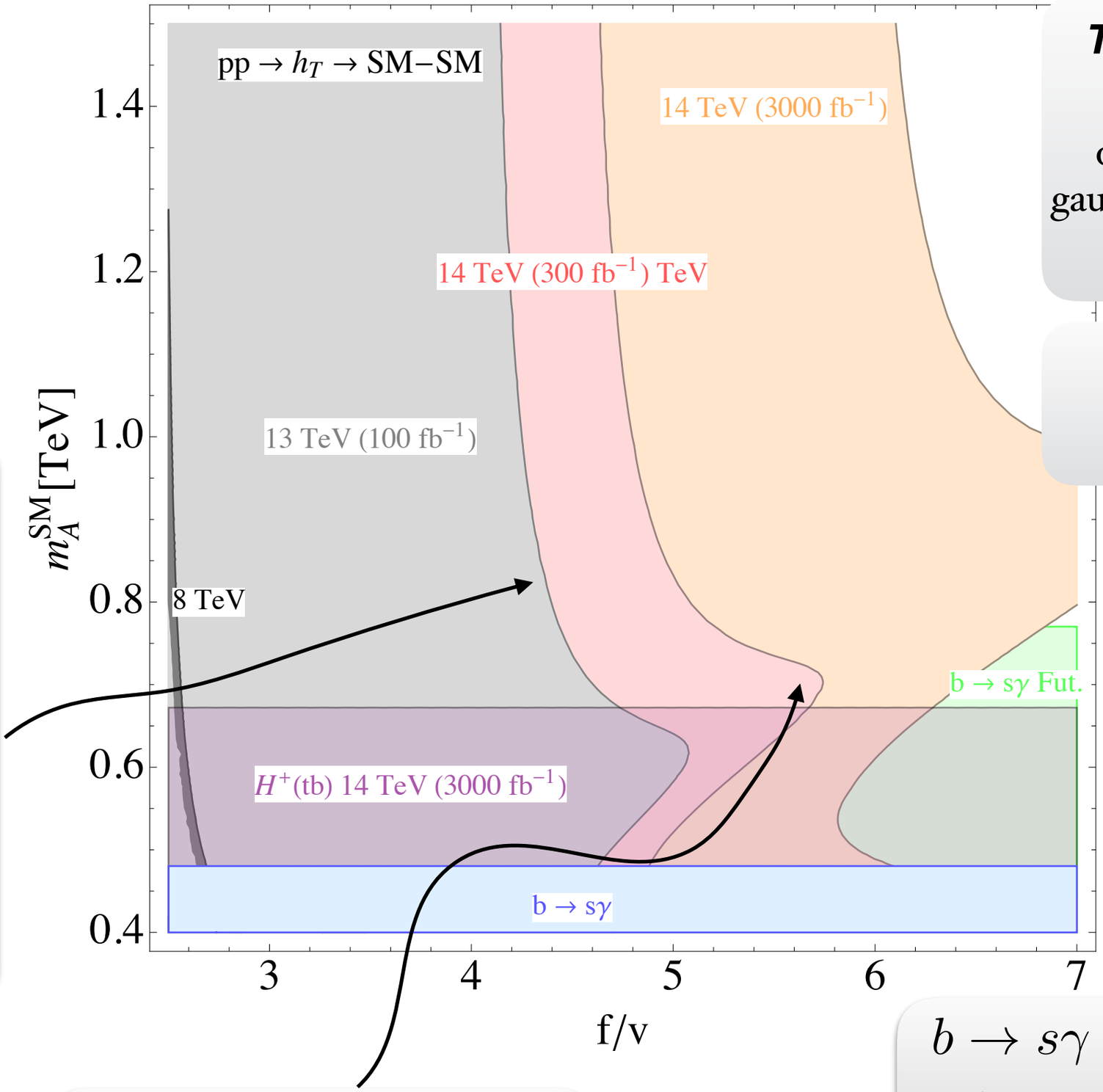

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$b \to s\gamma$ improvement in theory uncertainty

$H^+ \to tb$ up to 700 GeV but at HL

$t\bar{t}H\,, A$ associated production can be better but at least $300 fb^{-1}$

Summary

- Explicit breaking Z_2 with marginal (hard) operators enlarge the parameter space of the Twin

- Hard breaking has a different parametric of fine-tuning because it allows for large f/v but overshoots the Higgs mass

- SUSY UV completions can be constructed for both soft and hard breaking.

- "ugly" SUSY Twin models can have some gain in fine tuning compared to the soft Twin models

- The large f phenomenology resembles the one of the MSSM at low t_β